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Association Euratom - DTU, Technical University of Denmark, Department of Physics - Annual Progress Report 2011

R-Report

Edited by S.B. Korsholm, P.K. Michelsen, J.J. Rasmussen and C.M. Westergaard

April 2012

DTU Physics
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Abstract (max. 2000 char.):

The programme of the Research Unit of the Fusion Association Euratom – DTU, Technical University of Denmark (until 31-12-2011: Association Euratom – Risø DTU) covers work in fusion plasma physics and in fusion technology. The fusion plasma physics research focuses on turbulence and transport, and its interaction with the plasma equilibrium and particles. The effort includes both first principles based modelling, and experimental observations of turbulence and of fast ion dynamics by collective Thomson scattering. Within fusion technology there are activities related to development of high temperature superconductors. Other activities are system analysis, initiative to involve Danish industry in ITER contracts and public information. A summary is presented of the results obtained in the Research Unit during 2011.

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Preface

In 2006 seven parties, EU, Japan, Russia, China, USA, Korea and India, signed the agreement to build and exploit ITER, and to place ITER in Cadarache in France. ITER is a major experimental facility for the development of fusion as an energy source. It is expected that ITER will be ready for scientific exploitation in 2020. The mission of ITER is to demonstrate that nuclear fusion can be exploited as an energy source. ITER represents an unprecedented international cooperation in the field of science and technology. It also represents a valuable opportunity for cooperation between public research organisations and private industry. DTU participates in the internationally coordinated activities to develop fusion and sees itself as having a key role in facilitating the participation of Danish industries in the international fusion programme.

The principle being pursued with ITER is the fusion of hydrogen isotopes to form helium. To make the fusion process run at a significant rate the hydrogen gas must be heated to high temperatures where it ionises and turns into a plasma. The plasma must be confined to achieve suitable densities and sustain the high temperature. ITER will use a magnetic field for the confinement. While fusion holds the promise of providing a sustainable source of energy, which is environmentally sound, it also presents considerable scientific and engineering challenges. Key issues in the final steps towards realising fusion energy production include:

Improving the plasma energy confinement, that is the ratio between the energy of the plasma and the heating power required to sustain the plasma energy. Improving energy confinement implies reducing energy transport out of the plasma, which principally is due to turbulence. Thus, one of the key issues is to understand and control turbulence.

Channelling the energy of fast ions, produced in fusion reactions, into heating the bulk plasma without driving turbulence and without premature exit of the fast ions from the plasma requires understanding and control of the dynamics of the fast ions in interaction with other particles and with waves.

As of January 2012 the Technical University of Denmark (DTU) was reorganized, and the activities within fusion plasma physics research at Risø DTU have been included in the Department of Physics (DTU Physics) as a new section for Plasma Physics and Fusion Energy (PPFE). From January 2012 the Research Unit for the Contract of Association is hosted by DTU Physics and the Association is termed EURATOM – DTU. The main activities within the Research Unit will remain and possibilities for expanding these activities, including technical and scientific fields of relevance for the development of fusion energy, are being investigated. Contributions to investigations of materials (Tungsten and ODSFS) are included in the work plan for 2012-2013.

The main contributions from DTU to fusion research in 2011 have been: 1) Models for investigating turbulence and transport are continually improved, and benchmarked against experiments. 2) Central to understanding the dynamics of fast ions is temporally and spatially resolved measurements of the fast ion velocity distributions in the plasma. DTU, in collaboration mainly with EURATOM partners, is exploiting and developing millimetre wave based collective Thomson scattering (CTS) diagnostics at the ASDEX upgrade tokamak at the Max-Planck Institute for plasma physics in Garching (near Munich).

1 Summary of Research Unit activities

The activities in the Research Unit cover the main areas:

Fusion Plasma Physics, which includes:

- *Theoretical and numerical turbulence studies*. Turbulence and the associated anomalous transport of particles, energy and momentum is investigated using first principles based models and solving these by means of numerical codes in full toroidal geometry. These models are continuously being developed and benchmarked against experimental data and codes at other associations. The activities mainly focused on topics related to edge and scrape-off-layer (SOL) regimes of toroidal plasmas. The work is performed in collaboration with EFDA partners and in particularly with EFDA/JET.

- *Fast Ion Collective Thomson Scattering.* The research unit has taken the lead in the development and exploitation of fast ion collective Thomson scattering diagnostics for TEXTOR, ASDEX Upgrade (AUG) and ITER. These projects are carried out in close collaborations with the TEC† and AUG teams.

Other activities in 2011 have been:

- Investigations of high temperature superconductors for fusion reactors with special emphasis on cost of capacity assessments for toroidal field coils based on coated conductors.

- Participation in the EFDA programme on developing a multi-region global long term energy modelling framework called EFDA-TIMES.

- Activities to inspire Danish companies and make them aware of the possibilities of being a supplier to the construction of ITER.

- Activities on public information about fusion energy. This includes development and presentation of the “Danish Fusion and Plasma Road Show”.

The **global indicators** for the Research Unit in 2011 are:

Professional staff:	12.4	man-years
Support staff:	2.6	man-years
Total expenditure - incl. mobility:	2.42	Million Euro
Total EURATOM support:	0.62	Million Euro

† TEC: the Trilateral Euregio Cluster, a collaboration of FOM Institute for Plasma Physics, Holland; ERM/KMS, Belgium and Forschungszentrum Jülich, Germany.

2 Plasma Physics and Technology

2.1 Introduction

Plasma is a dense collection of free ions and electrons. The transitions from solids to fluids to gases are associated with increases in internal energy, the breaking of bonds and changes of physical properties. The same is true for the transition from a gas to a plasma. The plasma is rightfully described as the fourth state of matter, its physics differing as much from that of gases as that of solids does. As solid state physics is involved in a broad range of applications, it should be no surprise that plasmas have a wide range of applications, that their physics and chemistries are rich, and that the methods of generation and diagnosis are wide and complex.

Our activities in high temperature plasmas, aimed at developing fusion energy, are coordinated with the European EURATOM fusion programme through an agreement of association on equal footing with other fusion laboratories in Europe. Our EURATOM association facilitates extensive collaboration with other fusion research laboratories in Europe, crucial in the ongoing build-up of competencies at DTU, and gives us access to placing our experimental equipment on large fusion facilities at, e.g., the Max-Planck Institute for Plasma Physics in Garching, Germany. Our association with EURATOM also provides the basis for our participation in the exploitation of the European fusion research centre, JET, located in England. With its organisation of national programmes as EURATOM associations, the European fusion programme is a successful example of a large *European Research Area.* Our activities in high temperature plasma research and the development of fusion energy are introduced in subsection 2.1.1, and described in further detail in subsection 2.2 discussing turbulence and transport in fusion plasmas, and in subsection 2.3 discussing our use of millimetre waves for investigating the dynamics of fast ions in fusion plasmas.

2.1.1 Fusion plasma physics

Producing significant amounts of fusion energy requires a plasma with a temperature of 100 to 200 million degrees and densities of 1 to 2 times 10^{20} particles per cubic metre, corresponding to a pressure of 1 to 5 atmosphere. Unlike gases, plasmas can be confined and compressed by magnetic fields. At the required temperatures the plasma must be lifted off material walls to prevent the plasma from rapid cooling. This is done by suspending the plasma in a toroidally shaped magnetic field that also acts to balance the plasma pressure. The required temperature and densities have been achieved in the joint European fusion experiment, JET. The production of net energy adds the requirement that the energy in the plasma be confined at least on the order of six seconds. The confinement time is the characteristic time for cooling off if heating was switched off or, equivalently, the ratio of plasma energy to required heating power to sustain that energy content. Achieved confinement times are on the order of one second. Higher density could compensate shorter confinement time and vice versa, so a simplified statement of the target is that the product of temperature, density and confinement time should be six atmosphere $\times$ seconds and is currently one atmosphere $\times$ seconds. Progress towards the goal principally involves improving the confinement time or, equivalently, reducing the energy transport in the plasma. The energy transport in fusion grade plasmas is principally due to turbulence, one of our main research activities reported in subsection 2.2. Significant progress towards the goal is expected with the next step fusion experiment, ITER. In ITER significant fusion rates are expected and with that the fast ion populations in the plasma will increase dramatically compared with present machines. The fast ions may then influence the plasma significantly. As a consequence, the dynamics of fast ions and their interaction with the rest of the plasma is one of the central physics issues to be studied in ITER. This is another of our main research topics in fusion as reported in subsection 2.3.

The fields of turbulence transport and fast ions are closely knit. With steep gradients in plasma equilibrium parameters and with populations of energetic ions far from thermal equilibrium, fusion plasmas have considerable free energy. This energy drives turbulence, which in turn acts back on the equilibrium profiles and on the dynamics of the fast ions. The turbulence naturally gives rise to enhanced transport, but also sets up zonal flows that tear the turbulent structures apart and result in transport barriers. The edge transport barrier being most likely at the root of the poorly understood, but experimentally reliably achieved, high confinement mode (H-mode). This non-linear interplay between turbulence and equilibrium also supports transient events reminiscent of edge localised modes (ELMs) where energy and particles are ejected from the plasma edge in intermittent bursts.

This set of topics is the focus of our fusion plasma physics research: With first-principles based codes we seek to model the interplay between plasma turbulence, transport and equilibrium. This modelling is tested against experimental data in collaboration with other fusion plasma physics institutes. To elucidate the physics of fast ions and their interplay with turbulence, waves and transient events, we are engaged in the diagnosis of confined fast ions by collective Thomson scattering (CTS) at the ASDEX upgrade tokamak in the Max-Planck Institute for Plasma Physics in Garching, Germany.

2.2 Turbulence and transport in fusion plasmas

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The transport of heat, particles, and momentum across the confining magnetic field of fusion plasmas is one of the most important, but also most difficult areas of contemporary fusion research. It is well established that the “anomalous” transport component due to low frequency turbulence is usually far larger than the classical and neo-classical collisional transport, in particular in the edge region. Therefore, it is of highest priority to achieve a detailed understanding of anomalous transport and the underlying turbulence for the design of an economical viable fusion reactor based on magnetic confinement schemes. In spite of the dramatic progress in experiment, theory and computations during recent years, the quantitative understanding is still sparse and lacking predictive capability. Even fundamental phenomena such as transitions from low confinement regime (L-mode) to high confinement regime (H-mode), the profile resilience and the particle pinch that are routinely observed and classified experimentally have no generally accepted explanations.

The activities within plasma turbulence and transport are mainly focused on topics related to edge and scrape-off-layer (SOL) regimes of toroidal plasmas, but also investigations of core turbulence and transport are taken up. Generally, it is acknowledged that the conditions near the edge of the plasma are dictating the global performance, which seems natural since all transport has to go through the edge region, but certainly the coupling to the core plasma dynamics is essential. Theoretical and numerical investigations of first principle models form the majority of the work performed. We emphasize benchmarking of results and performance, both with other codes and analytic results (verification) and then also with experimental observations (validation).

The activities are fully integrated into the EURATOM fusion program, and we have active collaborations with several EURATOM laboratories on theoretical issues as well as on direct comparisons of our results with experimental observations. We are involved in the EFDA-JET program. We are actively participating in the Integrated Tokamak Modeling (ITM) Task Force on validation and benchmarking of codes as well as defining the ITM data structures. A. H. Nielsen is deputy leader for project IMP4. We have a significant involvement in the EFDA Topical Groups, and obtained task agreements particularly within the TG Transport. V. Naulin is deputy chair for TG Transport.

Several of our numerical codes are in use at different European laboratories, where they are employed for specific purposes, ranging from experimental comparisons to education of students.

The work carried out through 2011 includes:

Activities within TG Transport are discussed in sections 2.2.1 - 2.2.3. This covers participation in the planning and reporting of the TG Transport activities together with participation in specific tasks on the modeling and measurements in the SOL/edge region of toroidal devices.

Examples of the involvement in the ITM activities are provided in Secs. 2.2.4 and 2.2.5. The emphasis is here on the involvement in IMP4 on validation and benchmarking of codes as well as developing the Kepler workflows. Specifically, we organized an IMP4 Working Session at Risø DTU during May 2-13.

Investigations of the turbulence and transport at the edge and SOL of toroidal plasmas are continued by participating in experimental investigations and applying edge/SOL turbulence codes. These investigations are an integral part of our contributions to TG Transport. Section 2.2.6 describes the development of a global gyrofluid model for the edge/SOL and 2.2.10 discusses the application of new numerical schemes for global edge codes. The influence of finite Larmor radius (FLR) effects on the evolution of radial interchange motions of plasma filaments are investigated by a gyrofluid model (Sec. 2.2.7) showing a significant FLR effect on the filament dynamics. Sec. 2.2.9 is concerned with an extension of the ESEL model including ion temperature dynamics and lowest order FLR corrections, making it possible to simulate ion temperature fluctuations and profiles and compare with experimental results, see also Sec. 2.2.3. Finally, Sec. 2.2.11 describes ESEL simulations of the SOL turbulence in the EAST tokamak, showing fine agreement between simulations and experimental observations of density fluctuations.

The derivation of a fully consistent gyrokinetic collision operator for application in gyrokinetic models is briefly discussed in Sec. 2.2.8.

The involvement in the JET work program is summarized in Secs. 2.2.12 - 2.2.14. It is focused on areas of edge turbulence, transport and evaluation of electron temperature measurements.

2.2.1 Topical Group Transport

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The 2011 Topical Group (TG) Transport activities were dominated by the preparation of the 2012 EFDA workprogramme, which encompassed several preparatory meetings and two two-day general meetings to present and progress the 2012/13 programme in 11 workgroups.

The programme will focus on a number of transport related issues, like for example particle transport in the edge and try to develop and integrated approach, by f.x. taking the outer fuel cycle into account as well.

Another aspect of work was reporting of the 2011 activities, where a number of presentation meetings were organized. No dedicated TG Transport meeting took place in 2011, but there was participation in the US TTF.

2.2.2 WP11-TRA-01-01: Triggering of the L-H transition, L-H power threshold and ELM control techniques, role of momentum transport through the plasma edge

V. Naulin, A.H. Nielsen and J. Juul Rasmussen,
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The task was to perform experiments on ASDEX-Upgrade allowing measurements of the electric field components and the ion saturation current from which the radial transport of particles, the Reynolds stress and the radial flux of poloidal momentum were to be determined. Comparison with other diagnostics to investigate the changes in poloidal rotation of the plasma, including the intrinsic rotation during L-mode and Ohmic H-modes (in COMPASS) and the L-H or H-L transitions in the various operation modes should take place.

Additionally, the newly installed resonant magnetic perturbation (RMP) coils on AUG should be used to make comparative measurements of the above-mentioned parameters under their influence. Systematic studies were planned during various levels of gas puffing, i.e., when additional neutrals are inserted into the vessel. In this case the variation of momentum transport should be measured.

Further, it was to be investigated how a variation of NBI momentum input, while preserving the same NBI power, influences the adaption of the SOL flows and profiles, including blob behaviour under different particle, heat and momentum fluxes.

The fluxes in momentum and particle channel have been analyzed from probe measurements at AUG in limited and diverted L mode and in H mode shots. Analysis of the data with respect to ELM and inter ELM periods in case of the H mode shots has been done and statistics of the transport has been compared to the corresponding L mode shots. Similarities between L mode and ELM phase transport could be stated, while inter ELM H mode transport is statistically different and more similar to pure diffusive-like behaviour. This is in some agreement with recent statements on the inter-ELM power deposition profile width.

Current carrying filaments have been investigated and a turbulence code been adapted for use with a q-profile and a current filament as initial condition. The importance of induction is this situation has been demonstrated. The current filament behaviour could be reproduced by a simplified model and conditions for its establishment have been derived.

A publication regarding the results from AUG flux analysis is ready for submittal. However, the experimental time at AUG was very limited and shots with RMPs have not yet been achieved, nor has there been a scan in NBI power or gas puffing rate. On the theoretical side it turned out that filament behaviour cannot be calculated at present in flux-tube geometry. The investigation of different fluxes at the outboard midplane gives valid information for the test of L-H transition scaling models, which rely on turbulence transition mechanisms. The systematic study of plasma fluxes before and at the transition would allow conclusions on the strength of the different transport channels.

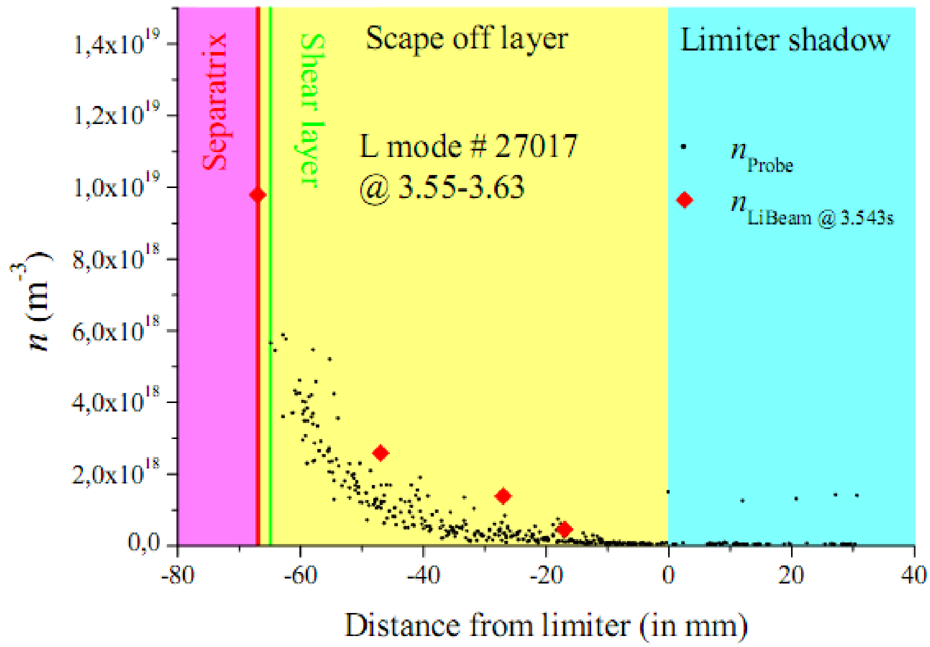

Figure 1. Probe data and Li-Beam data derived SOL density, showing good agreement between the measurements. AUG shot 27017.

2.2.3 WP11-TRA-05-01: Probe measurements and simulations in the SOL/edge

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The engagement in the field of simulating the dynamics in the SOL has mainly been concentrated in the area as specified in EFDA task WP11-TRA-05-01. The work was performed in collaboration with IPP Prague, ÖAW and IPP Garching.

The radial profiles of the derived ion temperatures (Ti) measurements using a Ball Pen Probe (BPP) at ASDEX Upgrade, shut number 26059 and 26060, was discussed intensively. Each radial point on the experimentally obtained profile consists of a large number of I-V characteristics, where Ti was derived from each one. As the sampling rates of the characteristics are (much) slower than the plasma frequencies observed in the SOL most of the derived Ti measurements had to be discarded resulting in a large uncertainty for the radial profile. During the discussion we created an averaged I-V characteristic for a given radial point from which Ti was derived, which significantly lowers the uncertainty. The resulting profile is relative flat compared to electron temperature and density profiles. One interpretation of this result is that ion temperature in the SOL varies slowly in both space and time.

The ESEL model assumes that ion temperature is constant in space and time. We have used the diffusivity and parallel loss parameter for ion dynamics in the electron temperature equation in ESEL as a first attempt of testing the hypothesis of assuming constant ion temperature in SOL; the result of that test was inconclusive. We have in the fall of 2011 thus developed a mathematical/numerical model extending the ESEL model to include finite ion Larmor Radius effects and thus included an equation for the ion pressure (see also Sec. 2.2.9). The model has been given the name HESEL (Hot Edge-Scrape-of-layer-Electrostatic). The derived model is energy conserving to the same order as ESEL.

HESEL is now under implementation and verification. In 2012 new measurements using the BPP at ASDEX Upgrade by IPP Prague and ÖAW are planned These will yield the ion temperature dynamics with a sampling frequency comparable to Langmuir probe diagnostic and be available for benchmark of the HESEL model.

For benchmarking the electron temperature dynamics as measured by the BPP at ASDEX Upgrade [1] we have made a number of very highly resolved ESEL simulations, see Figure 2. At present we are comparing experimental results with numerical results and a paper is scheduled for 2012.

During the week 23 – 27 May Risø DTU hosted the ESEL-week. The purpose of the meeting was to bring together people, who are using the ESEL code to discuss further progress of the model, hereunder how to include ion dynamics. The meeting had participation from, besides the host group, CCFE, UK (F. Militello), IPP Prague (J. Horacek), Laboratoire de Physique des Plasmas Belgian (M. Vergote).

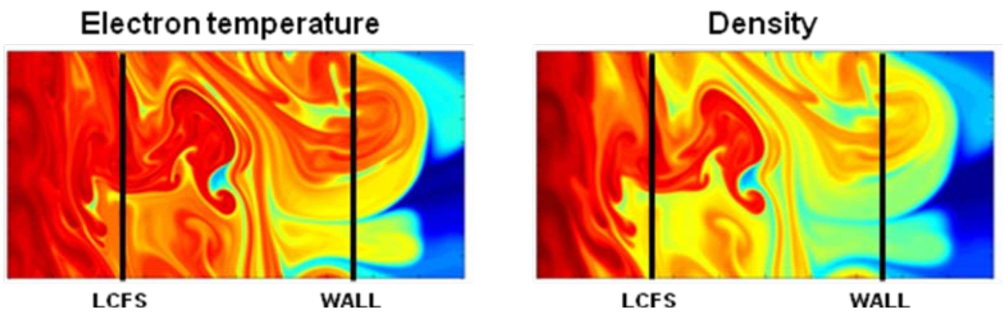

Figure 2. High resolution (2048x1024) ESEL simulation showing snap shots of the electron temperature (left) and density (right). Color scales are logarithmic to enhance the dynamics in the SOL and wall regions.

1. J. Horacek et al. Nucl. Fusion **50** (2010) 105001.

2.2.4 Integrated Tokamak Modelling Engagement

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The engagement in the Integrated Tokamak Modeling (ITM) has been concentrated in the project #4 in which DTU holds the deputy project leader position. Project #4 is responsible for numerical codes and associated Kepler workflows for instabilities, turbulence, and transport, as well as standards are maintained for the simple modules commonly used in transport modeling codes.

Progress was made in 2011 on projects of benchmarking the main turbulence codes under IMP#4, in which DTU is responsible for planning, quality checking and data comparison between individual codes. Workflow development and module maintenance were addressed on four of the ITM code camps and during the IMP4 working session at Risø DTU May 2 - 13. Four local IMP4 turbulence codes, both fluid and gyrokinetic, produced data for the core benchmark case (ATTEMPT, GENE, GEM, dFEFI) using fully the ITM framework. All the simulations have been performed on the HPC-FF. Even though the individual codes give to a certain degree comparable results still large differences are observed. Only one global turbulence code was able to do the core benchmark, the CENTORI code. The reason for this was two-folded; firstly there was a need to access additional HPC-FF resources, especially true for ELMFIRE. Secondly, stability problems occurred. It is foreseen that in 2012 the major part of the IMP4 global codes succeed in doing the core benchmark. The data were transferred to the Gateway and it was verified that they were in the format specified by the IMP4 standard. A set of Matlab routines has been created to compare the results from the different codes and a report based on these results is placed on the Gateway. It may be accessed by the IMP4 members, who participated in the benchmark.

The use of a SOL turbulence code to generate numerical fluctuation data to be compared with experimental Langmuir probes data (JET data) in a Kepler workflow is well under way. During 2011 the code ESEL, was modified as to be included in a Kepler workflow extracting basic electron and ion temperatures and electron density surface from the edge CPO. A subroutine to interpolate the model results at the location of the Langmuir probe has been written. The interpolated values will be written in the Langmuir CPO in the future. A numerical probe has been included into ESEL with a trajectory equal to that of the experimental counterpart. Unfortunately experimental data for this project was not available during the code camps in 2011, thus we were not able to demonstrate the usefulness and functionality of the workflow. This project will be continued in 2012.

2.2.5 Kepler workflows and interfacing with HPC-FF of TYR code family

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The TYR code family, consisting of flux tube geometry, three dimensional Braginskii fluid codes for edge turbulence was made capable of interfacing ITM Kepler workflows for parameter acquisition and outputs. To this extend the code base was changed to allow calling the codes as subroutines, and the code was ported to the gateway. An IMP4 actor of the TYR code was coded and included in a Kepler workflow. We tested initial reading of data from an ITM database on the ITM-Gateway.

2.2.6 Global gyrofluid model applicable to edge and scrape-off layer regions

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Motivated by the existence of steep gradients and high fluctuation levels in the edge and Scrape-Off Layer (SOL) regions of magnetically confined plasmas, a gyrofluid model was developed in which nonlinear terms in the gyrofluid moment equations and the Maxwell equations are not linearized. In previous models [1] only the ExB non-linearity was retained in the Vlasov equation and terms involved in polarization and magnetization effects in the Maxwell's equations were linearized. In the new model all non-linearities are retained. Also, gyroaveraging closures have been developed, which are truly global and are constructed with energy conservation in mind. The conserved energy is identical to the gyrofluid moment of the corresponding gyrokinetic energy theorem. Furthermore, no low β assumption is made. In previous models curvature effects were approximated using the low β approximation. In the present model all curvature effects are retained hence the model is therefore applicable not only to low β plasmas.

1. W. Dorland, Phys. Fluids B **5**, 812 (1993).

2.2.7 The influence of finite Larmor radius effects on the radial interchange motions of plasma filaments

J. Madsen, O.E. Garcia (Dept. Physics and Technology, University of Tromsø, Norway), V. Naulin, A.H. Nielsen, and J. Juul Rasmussen
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The influence of finite Larmor radius (FLR) effects on the perpendicular convection of isolated particle density filaments driven by interchange motions in magnetized plasmas is investigated using a two-moment gyrofluid model [1]. By means of numerical simulations on a two-dimensional, bi-periodic domain perpendicular to the magnetic field, it is demonstrated that the radial velocities of the blob-like filaments are roughly described by the inertial scaling, which prescribes a velocity proportional to the square root of the summed electron and ion pressures times the square root of the blob width. Due to FLR effects, the poloidal up-down symmetry in the particle density field observed in the zero Larmor radius limit is broken. The symmetry breaking implies a poloidal motion of the blobs in the B x gradB direction. At later times, the direction of the poloidal motion is reversed when the blob is decelerated. It is shown that the spatial structure of the blobs depends on the ratio of the ion gyroradius to the initial filament size ρ/σ. Blobs with $\rho/\sigma > 0.2$ remain coherent as they move through the scrape-off layer, whereas blobs with $\rho/\sigma < 0.1$ form plume-like structures that lose their coherence and eventually become fragmented. After having traveled approximately five times their initial widths, coherent blobs carry 2–3 times the particle density of fragmented blobs. It is shown that FLR effects reduce mixing, stretching, and generation of small spatial scales in the particle density field by setting up a sheared flow surrounding the blob. Figure 3 shows the time evolutions of the maximal particle density for blobs with identical initial blob sizes for different ion temperatures. The maximal particle density is increased when the ion temperature is increased, demonstrating the ability of FLR effects to reduce mixing and stretching of the blobs.

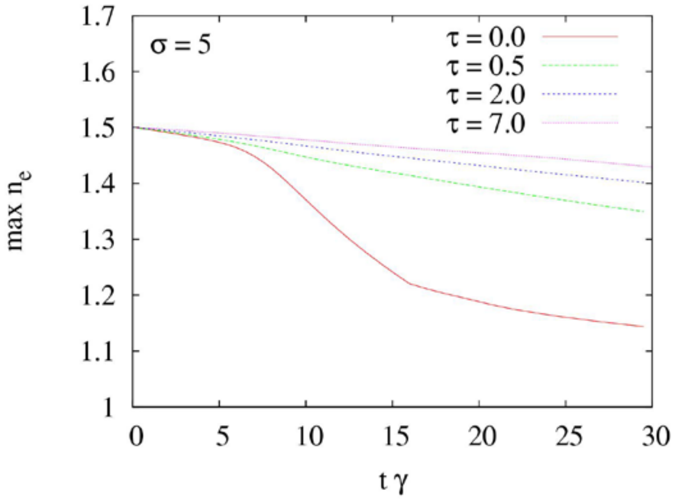

Figure 3. Maximal blob particle density as a function of time for blobs having widths 5ρ(τ=1), for different ion to electron temperature ratios τ.

1. J. Madsen et al., Phys. Plasmas **18**, 112504 (2011)

2.2.8 Gyrokinetic collision operator

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The goal is to derive a gyrokinetic collision operator, which for the first time allows independent dissipation rates of particles, pressure and turbulent momentum perpendicular to the magnetic field. Previous efforts in this direction have been concerned with the corrections arising from magnetic inhomogenities [1-4]. In this work we examine the correction that arises when the turbulent momentum part of the Landau collision operator is retained. Preliminary results have been obtained that are in agreement with fluid results [5] in appropriate limits. These results must be verified and generalized before publication.

1. P.J. Catto et al, Phys. Fluids, **20**, 396 (1977).
2. X.Q. Xu et al, Phys. Fluids B **3** (3), 627 (1991).
3. A. Brizard, Phys. Plasmas, **11** (9), 4429 (2004)
4. B. Li, Phys. Rev. Lett., **106**, 195002 (2011)
5. W. Fundamenski et al., Nuclear Fusion **47**, 417 (2007)

2.2.9 Inclusion of finite ion temperature effects in the ESEL model

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Experimental measurements report that the ion temperature is comparable to or even higher than the electron temperature in the scrape-off layer region [1]. Also, high fluctuation levels and the steep gradients are measured in the SOL regions. Therefore, an extension of the existing ESEL model [2] has been developed. The model includes ion pressure dynamics and is therefore able to describe the anisotropy between the electron and ion collisional pressure diffusion. In the direction perpendicular to the magnetic field the diffusion is proportional to the gyroradius of the each individual species. Whereas in the direction parallel to the magnetic field the diffusion rate is proportional to the individual sound speeds of ions and electrons [3]. Therefore, the classical diffusion coefficient of ions is an order of magnitude larger than corresponding electron pressure diffusion coefficient. In the parallel direction the picture is opposite and the electron pressure diffuses much faster than the ion pressure.

Furthermore, motivated by the combination of high fluctuation levels, steep gradients and finite ion temperature on the SOL region the lowest order finite Larmor radius corrections in the perpendicular momentum equation are included.

The extension is partly implemented in the ESEL code and testing is ongoing.

1. G. S. Xu et al., Phys. Plasmas, **17**, 022501 (2010)
2. O.E. Garcia et al., Phys. Rev. Lett., **92** (16), 165003-1 (2004)
3. S.I. Braginskii, Rev. Plasma Phys., **1**, 205 (1965)

2.2.10 New numerical schemes for global edge codes

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We expand the applicability of simulations of the edge of a tokamak plasma in the drift-fluid approximation, both in terms of simulating larger domains of the plasma, and more notably, to relax some of the standard assumptions made, e.g., that the fluctuations in magnetic field are so small as to be negligible: While this, and other similar assumptions are usually justified by the physics in states where no violent changes occur in the plasma, it is questionable whether they hold during, e.g., ELM events, where the current transported by the ELM might set up large fluctuations in the magnetic field. The strong anisotropy of the dynamics of a plasma in a magnetic field is usually used to define the geometry of the computational code, such that grid points are spaced far apart along the magnetic field lines, where dynamics are long range, and much closer apart across the magnetic field, where physics essentially work on the length scale of the gyroradius of the ions. Thus, fluctuating magnetic field changes not only the dynamics of the system, but the very geometry of the computational codes. In this project we will consequently develop new computational tools to change the geometry continuously in a simulation of tokamak plasmas, hopefully to foster a new understanding of the dynamics of ELM events, such that we might eventually better control these events. This is of crucial importance to the operation of ITER, where the projected energy deposit of ELMs on the wall of the chamber would lead to unacceptable damage of the vacuum chamber if not somehow controlled or prevented.

2.2.11 Simulation of boundary plasma turbulence on EAST

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To expand the experimental basis for our numerical codes, especially ESEL, we have been using experimentally obtained Langmuir probe data from EAST for benchmarking.

The transport of particles and energy in the plasma edge and in the scrape-off layer (SOL) of today magnetic-fusion devices in the low-confinement regime is mostly non-diffusive and occurs in the form of the intermittent convection of coherent mesoscale plasma structures [1]. It has been identified as a universal feature of turbulent fluctuations of boundary plasma, and constitutes a direct challenge to the confinement of fusion plasma.

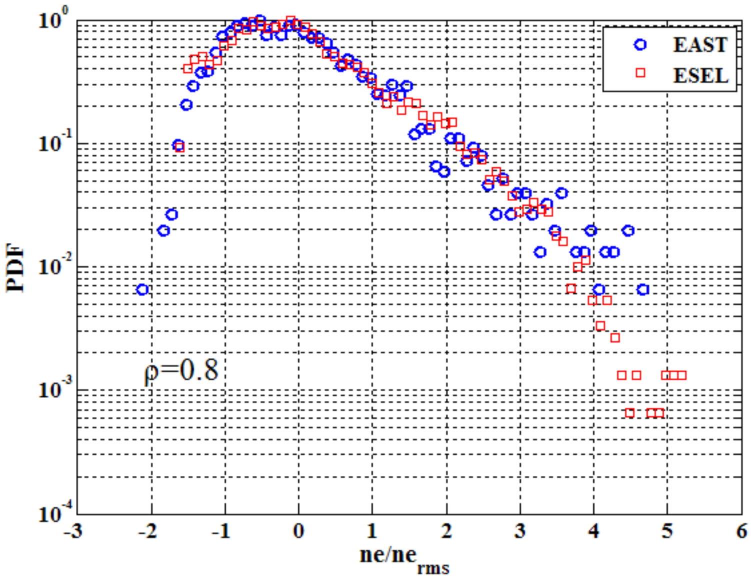

Figure 4. Comparison of the PDF of density fluctuation signal from experiment and simulation results at the radial position ρ=0.8. Here, ρ denotes the radial position normalized by the SOL width.

The two-dimensional interchange turbulence code ESEL (Edge-SOL electrostatic), which consist of a set of reduced fluid equations appropriate for the boundary region on the out-board mid-plane of a toroidally magnetized plasma, has been developed to describe the generation process of intermittent events in the boundary plasma [2]. In particular, the TCV result shows good agreement between the blob characteristics measured using reciprocating probes and simulation results [3]. In order to describe the formation and evolution of experimentally observed blob structures and to investigate their statistical properties on EAST, simulation work has been done with ESEL. As is shown in the Figure 4, rescaled probability distribution function (PDF) of normalized particle density fluctuations from ESEL simulations is in excellent agreement with experimental measurements on EAST. Both PDFs exhibit a tail at large positive amplitudes and a lack of such events on the negative side. This perfect comparison significantly indicates the commonly observed burst structures from probe measurements on EAST.

In conclusion, reasonable agreement between ESEL simulations and EAST experiments has been observed. These results are potentially important for the understanding for the intermittent turbulence transport in tokamak plasmas.

1. D. A. D'Ippolito, J. R. Myra, S. J. Zweben, Phys. Plasmas **18**, 060501 (2011)
2. O.E. Garcia, V. Naulin, A.H. Nielsen, et al., Phys. Rev. Lett. **92,** 16503 (2004)
3. O.E. Garcia, J. Horacek, R.A. Pitts, et al, Plasma Phys. Control. Fusion **48,** L1–L10 (2006)

2.2.12 JET collaboration

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The work performed on JET in 2011 can be divided in two large blocks: Work directly related to the exploitation of the ITER like wall and the more general ongoing efforts into understanding of fusion plasma properties, which include also the evaluation of data from previous campaigns.

2.2.13 Edge turbulence on JET

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In continuation of work done in earlier years studies in particle transport using modulated gas puffing have been proposed, the corresponding technical experiment to demonstrate feasibility of the technique will, however, first take place in 2012.

A focus of the investigations is the use of new, low performance L mode shot data to compare with the actual version of the ESEL code. Good results have recently been found for MAST and in scans it could be shown that the parallel losses are responsible for the observed SOL-width current scaling [Millitello et al., to be published]. Such a current scaling, which is observed on a number of smaller tokamaks, seems absent in recent JET experiments. Shots for a comparison are now being selected and detailed simulations are planned for 2012.

Within the JET modeling week, work was started to adopt the CYTO code, which simulates 3D cylindrical low temperature plasmas, to deal with fusion device SOL conditions. A first part of this ongoing project is the comparison and benchmarking of the code with 1D simulations by the SOLF1D code.

2.2.14 Participation in C28 at JET

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In 2011 Morten Stejner was on secondment at JET during C28 from November 21 to December 9. At JET he participated in work within the electron kinetics group to validate data from electron temperature diagnostics based on incoherent Thomson scattering measurements and electron cyclotron emission spectroscopy (the KE3, KE11, KK1 and KK3 diagnostics). Measurements with these diagnostics had previously shown discrepancies between the inferred electron temperatures, and the origin of these discrepancies was investigated based on both historical data and more recent data from C28 incorporating updated calibrations for both types of diagnostics. This work was continued during a second secondment period in early 2012.

2.3 Diagnosing fusion plasmas by millimetre wave collective Thomson scattering

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Millimetre waves, corresponding to frequencies in the 100 GHz range, permit probing and imaging on the centimetre scale and transmission of signals with bandwidths in excess of 10 GHz. Coherent sources are now available from the micro- to the single megawatt range, CW.

In the world of fusion, millimetre waves are used extensively both as a diagnostic tool and for heating and manipulating the plasma locally as well as globally. Central to achieving these objectives is the fact that millimetre waves, like laser light, can be projected in narrow focused beams, but unlike laser light, the millimetre waves can interact more strongly with the plasma.

At DTU, the millimetre wave collective Thomson scattering (CTS) diagnostic is developed and exploited with two diagnostic aims: for measuring the velocity distribution of confined energetic ions and for measuring the isotope composition (the so-called fuel ion ratio in a D-T fusion reactor) in fusion plasmas. The measurements are spatially localized with a resolution on the centimetre scale and have a temporal resolution on the millisecond scale.

The most energetic (or fastest) ions are the result of fusion reactions and auxiliary heating. Their interaction with the bulk plasma is the main mechanism by which the fusion plasmas reach and sustain the high temperatures of 100-200 million degrees Kelvin required for fusion. The considerable energy associated with the fast ions can also drive turbulence and cause instabilities in the plasma, and hence degrade the confinement of the plasma and of the fast ions themselves. Understanding and controlling the dynamics of fast ions are central tasks in the development of fusion energy and one of the main research topics for the next large fusion facility, ITER. It is a task we seek to contribute to by developing and exploiting the unique diagnostic capability of millimetre wave based collective Thomson scattering (CTS). The importance of the fast ion CTS diagnostic was further underlined by the fact that in 2008 the front end of a fast ion CTS diagnostic system was enabled in the new ITER baseline design. In 2009 the updated ITER Baseline Design was finally approved by the ITER Council. Risø DTU has developed the feasibility study and preliminary design of the ITER CTS diagnostic under EFDA task agreements. The work on CTS at TEXTOR and ASDEX Upgrade should be seen in the context of maturing the diagnostic for future use on ITER.

In addition to the use of CTS to diagnose fast ions, the diagnostic technique may also be used to measure the fuel ion ratio in a fusion plasma – both temporally and spatially resolved. This can be done by choosing particular scattering geometries and measure the effect of ion Bernstein waves and ion cyclotron motion on the CTS spectrum (see Section 2.3.5). This novel use of CTS is welcomed by the community since the measurement of the fuel ion ratio in ITER is a challenge with the current diagnostic set. The CTS based fuel ion ratio diagnostic was investigated and further developed under EFDA tasks under WP08/09, WP10 and WP11. The work of WP11 is further described in Sections 2.3.6 and 2.3.7.

The group has developed and implemented CTS diagnostic systems at the TEXTOR and ASDEX Upgrade tokamaks, which are located at the Research Centre Jülich and at the Max-Planck Institute for Plasma Physics in Garching, both in Germany. The upgraded CTS system for TEXTOR was brought into operation in 2005 where the first results were obtained. The operation of the CTS diagnostic was concluded in 2010 as the gyrotron used as a source for the CTS was decommissioned. However during 2011, results of the previous campaigns have been analyzed and published. The results from

TEXTOR are described in Sections 2.3.2 to 2.3.6. The operation of the CTS diagnostic at TEXTOR was conducted in collaboration with the TEC[1] consortium.

The CTS diagnostic system at ASDEX Upgrade has been operated in collaboration with the Max-Planck Institute for Plasma Physics in Garching. An overview of the experiments and significant hardware upgrades on ASDEX Upgrade is given in Sections 2.3.9 to 2.3.17.

The activities of the CTS group also involved development of new components, key to the CTS receiver as well as other millimetre wave diagnostics. During 2011 this has particularly included notch filter design described in Section 2.3.18 as well as the quasi-optical hardware described in Sections 2.3.14 and 2.3.15.

Finally, work on integrating experimental information from several fast ion diagnostics has been performed. The first analytical results of these efforts are given in Section 2.3.19.

2.3.1 EFDA tasks in 2011 for the CTS group

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During 2011, the CTS group has participated in the following EFDA tasks:

- WP11-HCD-01-04-01: NBI and LH off-axis CD efficiency: CTS measurements on AUG.
- WP-11-DIA-01-01-01: Experiments on confined fast particles.
- WP-11-DIA-01-03-01: Experiments of IBW modulations for fuel ion ratio measurement. This task has only participation from DTU and it has been extended to July 2012. The work is described in Sections 2.3.5 to 2.3.7. The task was a continuation of WP10-DIA-01-03: Measurements of fuel ratio, which was coordinated by Risø DTU. The conclusions of this task are described in Section 2.3.8.
- WP-11-MHD-01-02: Development of real time NTM stabilization system on AUG. The work on this task is primarily described in Section 2.3.17.

2.3.2 Overview of results from CTS at TEXTOR

S.B. Korsholm, H. Bindslev, V. Furtula, F. Leipold, F. Meo, P.K. Michelsen, D. Moseev, S.K. Nielsen, M. Salewski, M. Stejner, E. Westerhof, A. Bürger***
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The year 2010 marked the end of a decade long development and utilization of the CTS diagnostic system at TEXTOR. Independently of the work on CTS it had been decided to discontinue and decommission the FOM operated gyrotrons at TEXTOR. This in effect also led to the conclusion of the operation of the CTS diagnostic, which were relying on the 110 GHz gyrotron.

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1 TEC: The Trilateral Euregio Cluster, comprising Association EURATOM-Forschungszentrum Jülich GmbH, Institut für Plasmaphysik, Jülich, Germany; Association EURATOM-FOM, Institute for Plasma Physics, Rijnhuizen, The Netherlands; and Association EURATOM-ERM/KMS, Belgium.

While the CTS experiments on TEXTOR were discontinued in 2010, some of the efforts of the CTS group in 2011 have been devoted to analysis of the data obtained in the past TEXTOR CTS campaigns. The areas covered was isotope composition experiments (Sections 2.3.5 and 2.3.6), fast ions and RMP (Section 2.3.4), and a novel method of checking transmission line alignment using sawteeth (Section 2.3.3).

The CTS work at TEXTOR over the years was always dependent on the collaboration with the FOM ECRH team operating the gyrotron source and the FZ Jülich TEXTOR team.

2.3.3 Alignment check of quasi optical receiver mirrors of the CTS diagnostic by measurements of sawtooth oscillations

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Alignment of the CTS diagnostic's mirrors is of a large importance for the utilization of the diagnostic, since it determines the location of the overlap volume and the scattering geometry. On TEXTOR, the elevation angle of the receiver mirror is primarily responsible for the radial position of the overlap volume. However, previously elevation angle alignment could be checked only during in-vessel works, typically once a year. A new method of checking the elevation angle alignment was developed and successfully implemented on TEXTOR. Figure 5 demonstrates the principle of the method. The receiver is operated in the electron cyclotron emission (ECE) radiometer regime and the gyrotron is off. The magnetic field is set so that the ECE resonance layers and the $q = 1$ surface is within the receiver frequency bandwidth. Operating in this regime, the receiver is sensitive to changes in electron temperature and is therefore capable of diagnosing sawtooth oscillations, which have distinguishably different signatures inside and outside the $q = 1$ surface. Sweeping the elevation angle of the receiver mirror, intersection points between the resonance layer and the $q = 1$ surface can be found for every receiver channel by means of ray-tracing. Since the $q = 1$ surface has a plane of symmetry about $z = 0$, the calculated z-coordinates should also be symmetric about $z = 0$. The bisection point exactly halfway between the calculated values of the intersection positions should lie at $z = 0$. On TEXTOR, by means of this method a small elevation angle misalignment of $0.9^\circ \pm 0.1^\circ$ was found. The method does not rely on any reconstruction technique of the magnetic equilibrium and is based on two assumptions: firstly, the $q = 1$ surface is symmetric about $z = 0$ and secondly, the equilibrium does not change throughout the elevation angle sweep. The first assumption was confirmed by numerous incoherent Thomson scattering measurements. The second assumption could not be validated by direct measurements; instead the sawtooth period was used as an indicator of stability of the experimental conditions. Indeed, the sawtooth period during the alignment check in TEXTOR was 37 ms with variance of 4%.

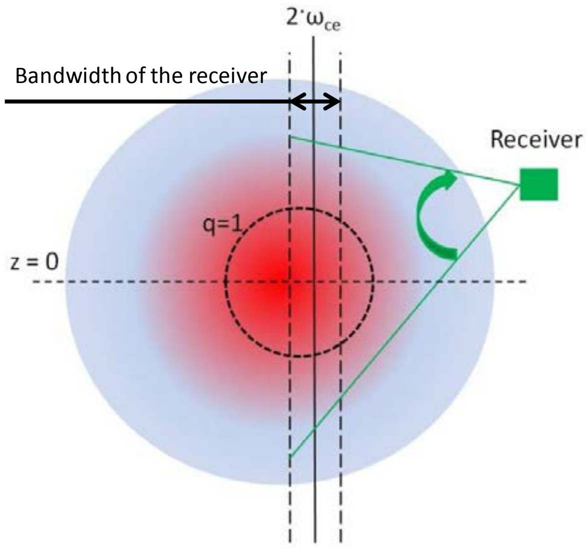

Figure 5. A sketch illustrating the principle of post factum elevation alignment check, using the CTS receiver as an ECE radiometer. The q = 1 magnetic surface is shown as a black dashed circle; black vertical and dashed lines show the lower- and the upper-most positions of electron-cyclotron resonance which the receiver is sensitive to; the green box denotes the steerable mirror of the receiver, solid green lines represent the beam of EC waves propagating into the receiver; the green arrow indicates the direction of the receiver mirror sweep.

2.3.4 Influence of resonant magnetic perturbations on fast ion confinement

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Edge localized modes (ELMs) are considered dangerous for future ITER operation, thus methods of controlling them are under development. One of them is based on decreasing the plasma pressure gradient at the edge so that the value of the gradient is insufficient for triggering the mode. However, the total particle and energy transport remains small in comparison with L-mode confinement regime. This is achieved by applying external radial resonant magnetic perturbations (RMP) to the equilibrium magnetic field at the edge. Since the perturbations are created by a discrete set of coils, the RMPs may also affect core localized fast ions. The CTS experiments devoted to the experimental check of this hypothesis were performed on TEXTOR. The effect was studied by applying notches to the co-I_p NBI power in the different measurement periods: without RMP (reference), without RMP and with a decaying (2, 1) island, with RMP in (6, 2) configuration working in the DC mode. The RMPs were created by the Dynamic Ergodic Divertor (DED). The superimposed time traces of normalized spectral power density (SPD) from the fast ion CTS channel with a frequency shift of 800 MHz from the probing frequency are shown in Figure 6.

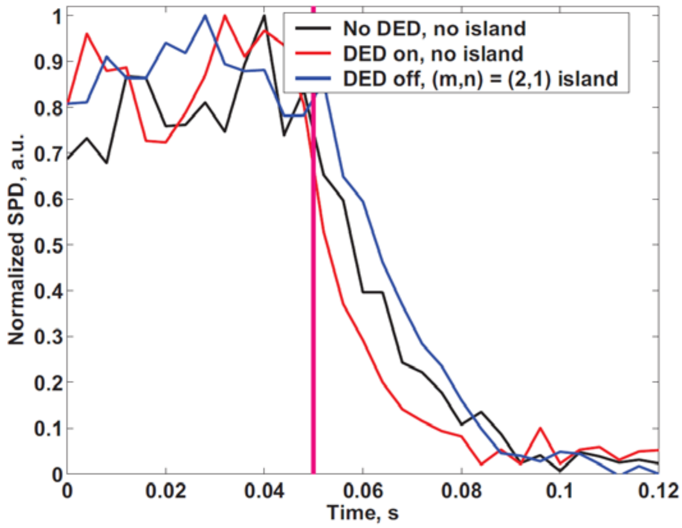

Figure 6. Comparison of the normalized time traces for three different scenarios: without RMP and magnetic island (black line), with RMP and without magnetic island (red line), without RMP in presence of decaying magnetic island (blue line). The vertical line denotes a moment when NBI is switched off.

The time traces after the NBI has been turned off are fitted with the exponential function: $S \propto \exp(-\nu \cdot t)$. The fitting coefficients for the reference scenario and the scenario with the decaying island were found close to each other: 59.3±4.4 1/s and 59.6±3.9 1/s, respectively. For the RMP scenario, the coefficient was higher: 79.6±3.7 1/s. Assuming that the decay of the fast ion signal is due to collisions and that temperatures in all three measurements were the same ($\nu \propto n$) the ratio between the fitting coefficients in the different scenarios should be equal to the ratio of central densities in the corresponding measurement periods: $\nu_{reference}/\nu_{RMP}$ = 0.745 and $n_{reference}/n_{RMP}$ = 0.7±0.02; ν_{island}/ν_{RMP} = 0.75 and $n_{reference}/n_{RMP}$ = 0.75±0.02. Thus, no additional fast ion transport due to applied RMP was observed. However, it is important to mention that the current in the DED windings was approximately one order of magnitude smaller than in usual RMP experiments, which could reduce an effect of additional transport. The low coil current was due to operational reasons.

2.3.5 Plasma composition measurements by CTS

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For scattering in the plane perpendicular to the magnetic field in the plasma CTS spectra contains characteristic peaks at frequency intervals corresponding to the ion cyclotron frequencies of the dominant ion species in the plasma. The peaks, so-called ion cyclotron structures, are created by the effects of ion cyclotron motion and weakly damped ion Bernstein waves on the fluctuation spectrum resolved by the CTS measurement. The ion cyclotron structures are highly sensitive to properties of thermal ion populations in the plasma such as ion densities, temperatures and rotation velocities. In particular the ion cyclotron structures allow access to information about the plasma composition which is of interest for measurement of the fuel ion ratio, n_T/n_D, in burning fusion plasmas where such measurements would be important for basic plasma control and machine protection. However, the peak separation in the ion cyclotron structure is well below the band width of the filter bank channels in the standard receiver setup used in fast-ion measurements –

see the simulated example in Figure 7 below. In order to exploit the ion cyclotron structures new acquisition and analysis techniques for CTS measurements with high frequency resolution were therefore developed in 2009-10 [1], and results from the first proof of principle experiments demonstrating the ability to resolve the ion cyclotron structures were published in the beginning of 2011 [2]. During 2011 we have further published the first detailed quantitative analysis of CTS spectra with ion cyclotron structures, we have completed a sensitivity studies on fuel ion ratio measurements by CTS on ASDEX Upgrade and ITER, and we have upgraded and started to commission the CTS system at ASDEX Upgrade for plasma composition measurements based on ion cyclotron structures. The following sections provide more detailed descriptions of work performed within these areas in 2011.

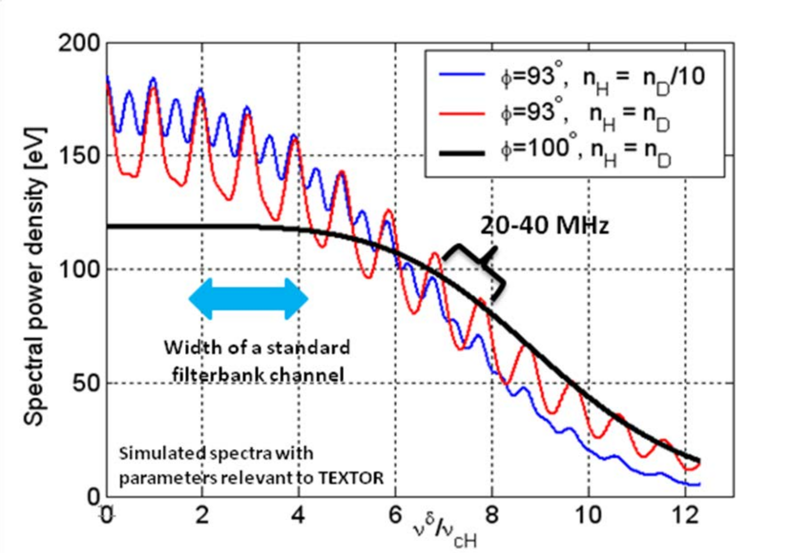

Figure 7. Simulated spectra illustrating the sensitivity of the ion cyclotron structure in CTS spectra to plasma composition and to the resolved angle, $\Phi=\angle(k^{\delta}, B)$, between the magnetic field and resolved fluctuation wave vector. The frequency scale is normalized by the hydrogen ion cyclotron frequency, and the ion cyclotron structure shows up as peaks form peaks separated roughly by the cyclotron frequency of the most common ion species in the plasma – which is well below the frequency resolution of the filter bank used for fast-ion measurements.

1. M. Stejner et al., “Collective Thomson scattering measurements with high frequency resolution at TEXTOR,” Review of Scientific Instruments, **81**, 10D515 (2010).
2. S.B. Korsholm et al., “Measurements of Intrinsic Ion Bernstein Waves in a Tokamak by Collective Thomson Scattering,” Physical Review Letters, **106**, 165004 (2011).

2.3.6 Data analysis for plasma composition measurements by CTS at TEXTOR

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Quantitative analysis of CTS data requires the measured spectra to be fitted with a forward model for CTS. Fits to spectra with ion cyclotron structures are computationally demanding due to the high frequency resolution in such spectra and the number of free parameters to be considered when fitting the bulk feature in CTS spectra. New fitting routines have therefore been developed for this task, and during 2011 these routines developed and benchmarked to a state which now permits routine interpretation of measured spectra. In addition, a parallelized version has been implemented on Linux cluster at DTU, which has significantly reduced the time required fit and interpret the measured CTS spectra.

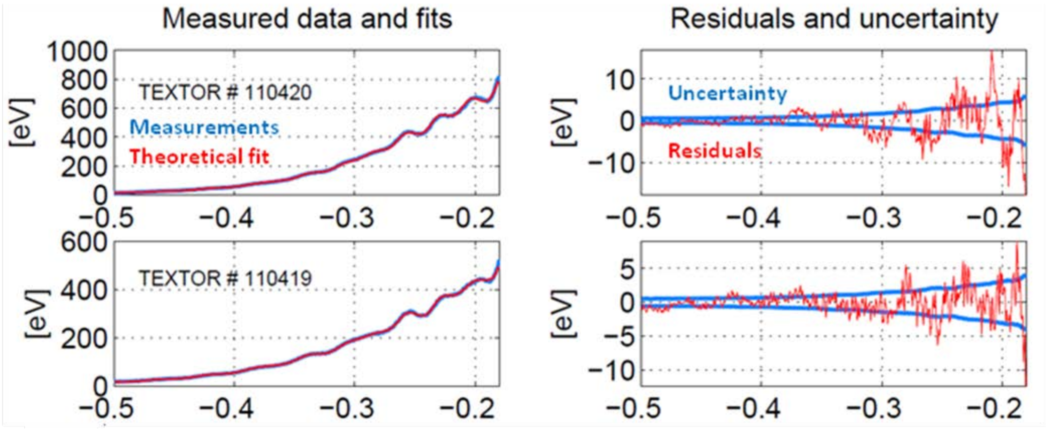
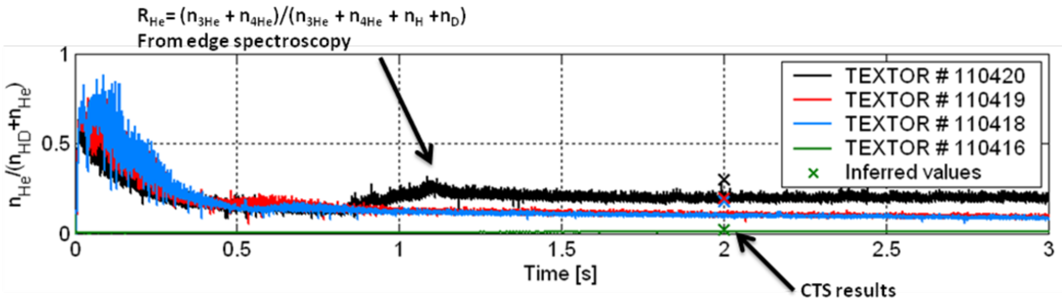


Figure 8. Left: measured spectra and theoretical fits for two discharges at TEXTOR for which the CTS spectrum contains ion cyclotron structures. Right: Residual in the fits compared to the measurement uncertainties for the same discharges.

Based on these analysis routines the first quantitative analysis of CTS spectra to infer the plasma composition from ion cyclotron structures was submitted to and accepted by PPCF during 2011 [1] (published early 2012). Figure 8 show a few examples of fits obtained in this work to CTS spectra measured at TEXTOR. This work also includes a comparison between ^{3}He densities measured by CTS in the plasma core and by passive charge exchange spectroscopy (CXRS) at the plasma edge. Here it was found that the two measurements show the same trends and give nearly the same ^{3}He densities illustrating that CTS can also be used to detect light impurities in fusion plasmas - see Figure 9 for a comparison of the CTS and CXRS results.

The data obtained at TEXTOR during 2010 includes CTS spectra with ion cyclotron structures measured in neutral beam heated discharges, the first temporally resolved measurements of this type and data taken during radial scans of the CTS scattering volume position. Analysis of these data can provide radial profiles of the plasma composition and ion temperatures, and the data from neutral beam heated discharges will permit detailed comparison to ion temperature measurements by active charge exchange spectroscopy. Results from such analysis, performed during 2011, are in preparation for publication.



		110416	110418	110419	110420
$n_{3\mathrm{He}}$ $[10^{18}\mathrm{m}^{-3}]$	from CTS	0.007	2.72	2.73	5.4
R_{He}	from CTS	0.02	0.18	0.20	0.30
R_{He}	from edge spectroscopy	0.01	0.10	0.11	0.20

Figure 9. ^{3}He densities measured at the plasma edge by CXRS and in the plasma core by CTS. Despite aggressive fueling with ^{3}He during the start-up phase and continuous fuelling in discharge 111420 the plasmas were dominated by recycled hydrogen and deuterium from the vacuum vessel walls. The CTS and CXRS results are similar and show the same trends, and the differences could indicate different plasma compositions in the core and edge regions.

1. M. Stejner et al., “Measurements of plasma composition in the TEXTOR tokamak by collective Thomson scattering,” Plasma Physics and Controlled Fusion, **54**, 015008, (2012).

2.3.7 Sensitivity studies for plasma composition measurements by CTS on ITER, ASDEX Upgrade and JET

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The revised ITER baseline design includes an enabled fast-ion CTS system. A fuel ion ratio CTS diagnostic would be conceptually very similar and could in principle be integrated in and operated in conjunction with the fast-ion system. During 2011 we expanded and published a previous sensitivity study for a CTS fuel ion ratio diagnostic on ITER. The study, which was initiated under EFDA contract WP10-DIA-01-03 and partly reported in the 2010 annual report, was expanded to include a wider range of background levels, probe powers and measurement positions as well as detailed tests and benchmarking of the fitting routines used for plasma composition measurements by CTS. The results were prepared for publication and submitted to Nuclear Fusion in 2011 and were published in early 2012 [1]. In this work we calculate the expected accuracy of fuel ion ratio measurements by CTS within the framework of a Bayesian least squares method of inference commonly used to interpret CTS measurements. This approach accounts for the sensitivity of the CTS spectrum as well as uncertainties in both the CTS measurements and information about nuisance parameters from other diagnostics, and it can be shown to make optimal use of the available information when noise and uncertainties are normally distributed. An example of results from this study is shown in Figure 10 which gives the expected relative accuracy of fuel ion ratio measurements by CTS on ITER as a function of the fuel ion ratio itself and the position of the CTS scattering volume along the plasma minor radius. The requirements for fuel ion ratio measurements on ITER are given as 20% relative accuracy for n_T/n_D = 0.01 to 10, for r/a < 0.85 with temporal resolution of 100 ms and spatial resolution of a/10 where a is the plasma minor radius. The requirements on spatial and temporal resolution can be fulfilled by a CTS system, and Figure 10 indicates that the requirements on accuracy and range could be fulfilled for the ITER standard operating scenario both in the plasma core (red crossed circle) and across the plasma radius.

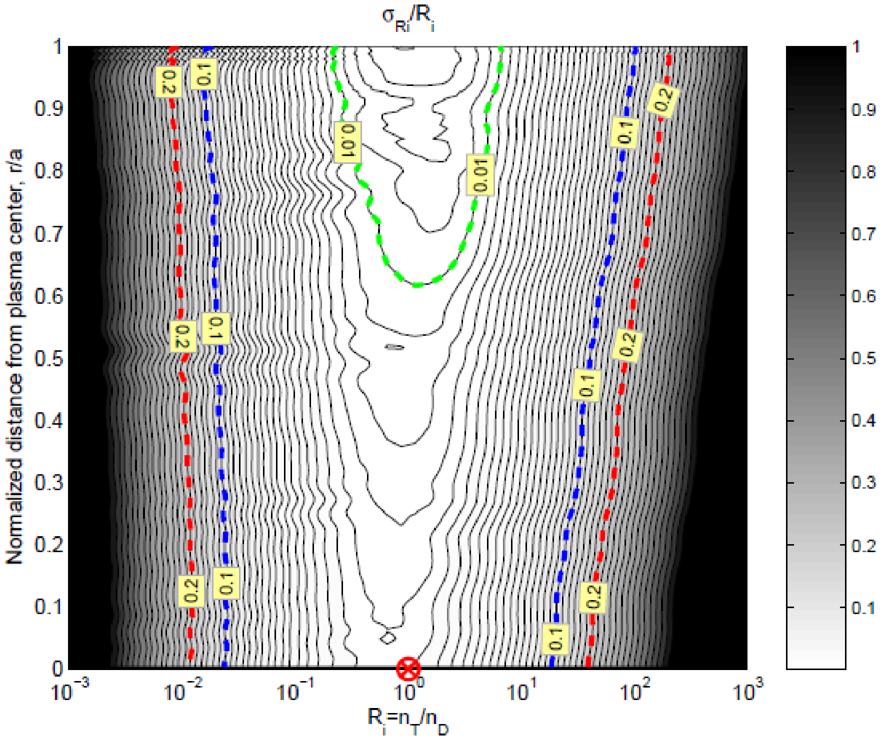

Figure 10. Expected relative uncertainty in measurements of the fuel ion ratio, $R_i= n_T/n_D$, in ITER as a function the fuel ion ratio and the position of the CTS scattering volume given as distance from the plasma center normalized by the plasma minor radius, a. In the plasma core, r/a=0, the relative uncertainty is within the 20% level on the range 0.01 < R_i < 40. Outside the core this range can be somewhat wider due to the lower temperature there.

Similar studies were also performed to assess the potential accuracy of plasma composition measurements by CTS on ASDEX Upgrade and JET. Such measurements are expected on ASDEX Upgrade with the hardware upgrades to be discussed below, and the sensitivity studies performed in 2011 evaluated the required probe power, background levels, integration time, bandwidth and frequency resolution and thereby provided valuable information for the planning of these experiments. The sensitivity study for JET was motivated by the possible DT campaign on JET in 2015. A DT campaign on JET would be the only realistic opportunity to benchmark all the candidate fuel ion ratio diagnostics on current machines under realistic operating conditions, and this would further provide a good opportunity to test a CTS diagnostics with a design similar to that of the planned ITER CTS diagnostic. Our study aimed to assess the feasibility of fuel ion ratio measurements by CTS on JET during DT operation and to provide initial design consideration for such a diagnostic. Results of the study indicate that it would be possible to build a CTS diagnostic on JET which could provide accurate fuel ion ratio measurements within certain ranges of temperature and density – see Figure 11 for an example. These results and the preliminary design consideration were submitted as a diagnostic proposal to the EFDA JET team.

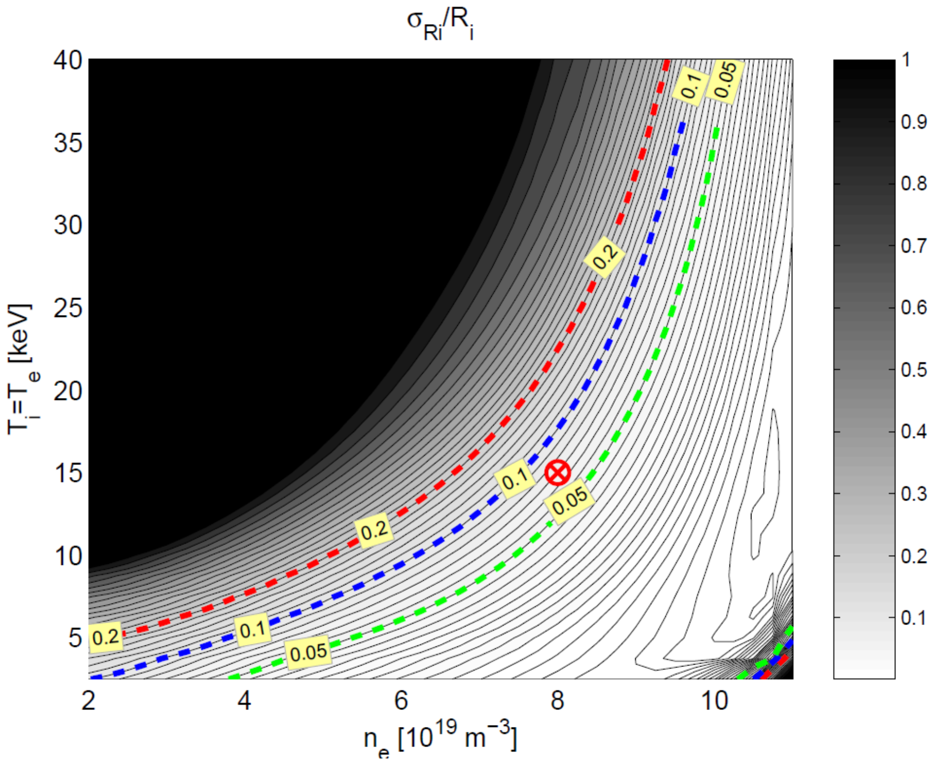

Figure 11. Expected relative uncertainty in measurements of the fuel ion ratio, $R_i = n_T/n_D$, on JET a function of plasma density and temperature. The results indicate that reasonable accuracy can be attainable for wide ranges of temperatures and densities, but likely not in so-called hot ion H-modes where the density is kept low in order to achieve very high ion temperatures.

1. M. Stejner et al., "The prospect for fuel ion ratio measurements in ITER by collective Thomson scattering," Nuclear Fusion, **52**, 023011, (2012).

2.3.8 Comparison of fuel ion ratio diagnostic techniques for ITER

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*(*ENEA Frascati (I), **CNR-Milano (I), ***Uppsala University (S), ****FOM DIFFER (NL), *****FZ Jülich (D))*
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During 2011 six associations worked together to shed light on the different performance aspects of four different potential fuel ion ratio diagnostics for ITER: Charge Exchange Recombination Spectroscopy (CXRS), the High Resolution Neutron Spectrometry (HRNS: TOFOR and MPRu), and the Radial Neutron Camera (RNC), and finally Collective Thomson Scattering (CTS).

In order to compare the performances of the different diagnostic techniques on an equal footing it was agreed to use the ITER Scenario 2 as reference and to vary the main plasma parameters as presented in the table below:

Parameter	Range	Reference value (S2)	Comment
nT/nD	$10^{-3} – 10^{2}$	1	
Ti	2 – 40 keV in steps of 2 keV	23.49 keV	
Te	See comment	26.96 keV	Scale withTi
Ne	3, 8, 11, 14, 19 10^{19} m^{-3}	11.29 10^{19} m^{-3}	

The uncertainties on the determination of any other parameters used in the analysis are in accordance with the ITER diagnostic database. Each group should justify the further assumptions taken in the calculations.

The target for the calculations was a relative accuracy of 20% and a time resolution of 100 ms. In the case of spatially resolved measurements, the results for the measurement point closest to the plasma center are presented.

Furthermore, in the case of partially or fully included diagnostics (in the ITER baseline) the geometries, apertures, and equipment follow that of the ITER baseline.

In Figure 12, we present a summary of the results for the reference scenario of the calculations. More details and summary figures for the other densities can be found in the *Final report for the EFDA Fuel ion ratio task WP10-DIA-01-03*.

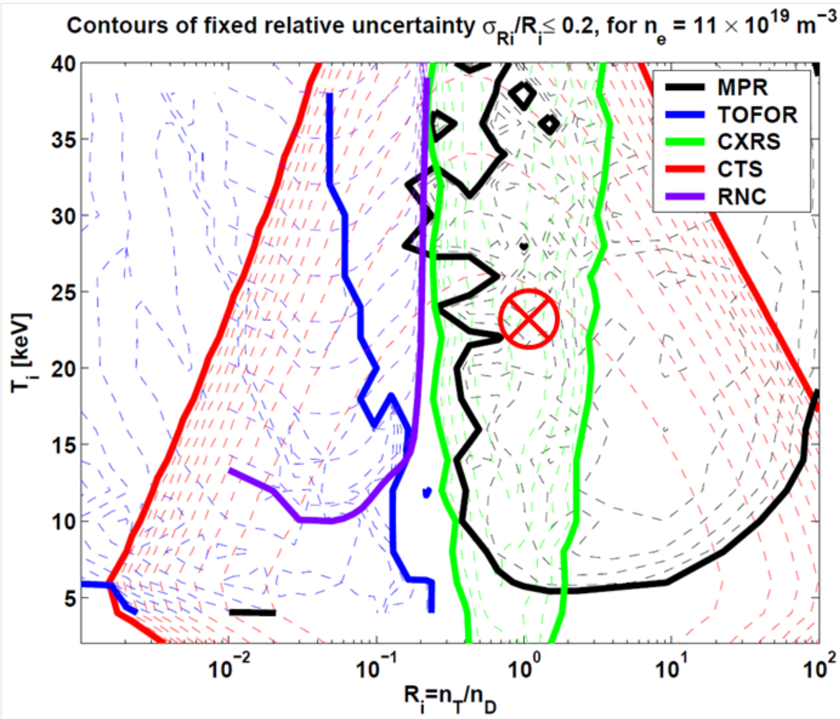

Figure 12. Relative uncertainty of five diagnostic systems for measurements of the fuel ion ratio in the core of ITER as a function of fuel ion ratio and ion temperature. The cross marks the ITER Scenario 2. Solid lines represent the 20% accuracy limit at the innermost measuring volume for each diagnostic. Regions of accuracy better than 20% is filled by either contours or dashed lines.

For CXRS the innermost position is at r/a=0.3. For HRNS there is no spatial resolution, but since it depends on the fusion rate, it gives primarily a measure of the centre of the plasma. For the RNC the radial location for the spatially resolved measurement is at r/a~ 0.01. The analysis of the RNC performances has been restricted to fully thermal plasmas (i.e. no NBI). For CTS the measurement volume is at the center r/a=0, while the spatial resolution is in the order of a/10. The CTS diagnostic is not dependent on NBI on/off, but is sensitive to the ion temperature.

The concluding considerations from the task can be summarized in these points:

- The diagnostics will operate inside different plasma parameter regimes
- Some diagnostics have no spatial resolution, while others have.
- Some have measurements in the center while others measure at r/a=0.3
- Some diagnostics are affected by NBI, some are helped by or are dependent on NBI, while NBI is of no significant to others
- Some diagnostics are fully and some are partly included in the ITER baseline
- Most of the diagnostic systems need some technological development to be ready for ITER

Hence we conclude that the optimum diagnostic set for fuel ion ratio measurements on ITER depends on an evaluation which is not only scientific.

2.3.9 Overview of activities of the CTS at ASDEX Upgrade

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ASDEX Upgrade (AUG) is a medium sized tokamak with a very large power density of auxiliary heating. AUG is equipped with 8 neutral beam injectors (total of up to 20 MW), 7 MW of ion cyclotron resonance heating, and up to 2.7 MW of electron cyclotron resonance heating (ECRH). AUG is well suited for fast ion physics exploitation due to its high power density and to its large suite of fast ion diagnostics which includes the CTS. Localized measurements of the fast ion distribution function hold the potential of accessing the physics of fast ion transport, including the physics of energy dependant transport. In addition, knowledge gained from CTS experiments on today’s machines will of course contribute to the development of the technique for future reactor type experiments. Therefore, the CTS installed on AUG is a stepping stone for the CTS on ITER.

CTS experiments on AUG have uncovered unexpected secondary emission (SE) which affects the diagnostic’s ability to measure fast ions. Some SEs studied in past campaigns were already identified and the understanding of their reproducibility under certain operating regimes exists. Improvements in analysis techniques and diagnostic methodologies such as fast gyrotron modulation, described in Section 2.3.13, have significantly improved the understanding of these emissions (see section 2.3.11). However, some SE still needs to be understood, and they most likely have more than one physics explanation.

Two major CTS hardware upgrades have been implemented in 2011 (see section 2.3.14): installation of an additional CTS system (formerly located at TEXTOR) in Section 2.3.15, and coupling a 5 GHz bandwidth acquisition card to the first CTS system enabling measurements of both the CTS receiver and fast card simultaneously (see 2.3.16). Both hardware upgrades have the potential to shed light on the physics of the secondary emissions in future experiments and possibly provide a solution.

2.3.10 Diagnostic performance experiments

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Before any physics exploitation experiments, diagnostic performance experiments are required and were carried out during the beginning of the 2011 campaign. Beam alignment and the beam quality is one of the important prerequisites for a CTS diagnostic. This is achieved by sweeping a beam across the other. Figure 13 shows the comparison between the beam overlap from calculations based on ray tracing using prior alignment of the antenna (in red) and the scattered radiation from experiment (in blue). The latter is linearly dependent to the overlap in steady-state plasma conditions. The figure confirms the agreement in the angle corresponding to the maximum overlap to within 1°. In addition, the experiment also confirmed the beam quality where no side lobes have been observed.

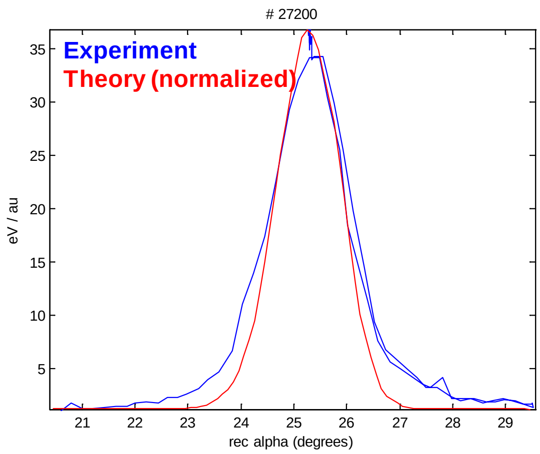

Figure 13. As a function of receiver antenna angle, the blue line denotes scattered radiation of a central channel during an angle scan of the receiver beam across the probe beam. In red is the normalized theoretical beam overlap value (integral of normalized beam intensity of the receiver & probe beam) from ray tracing.

2.3.11 Secondary emission investigation experiments

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Improvements of the CTS diagnostic techniques in 2011 such as the fast probe power modulation described in Section 2.3.13 have increased the CTS diagnostic's ability to resolve some types of anomalous signals or secondary emissions (SE). One example of SE can be seen in the spectral power density plot in Figure 14. The graphs show distinct peaks localized in frequency on each side of the gyrotron frequency. Their intensity is strongly correlated to the ELM cycle. These peaks are believed to be caused by a lower hybrid type of instabilities which were also observed in CTS experiments on TEXTOR and W7-AS [1] (see also Section 2.3.12). CTS experiments on AUG in 2011 have found that the emission levels of these SE entering the CTS receiver can be above a few keV and are not correlated to the overlap thus suggesting that this radiation is not localized in the overlap region and thus their intensity must be very large. The literature on the theory of these waves state that they can originate by either relative cross-field drift between electrons or and ions (LH-drift instabilities) or driven by gradients in the perpendicular fast ion distribution.

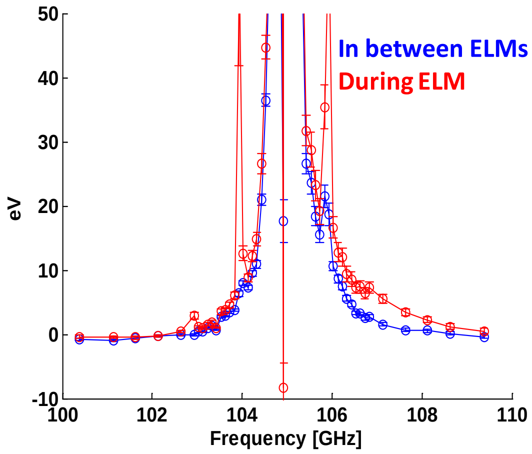

Figure 14. Spectral power density for an NBI heated AUG plasma discharge during an ELM event (in red) and in between ELMs (in blue).

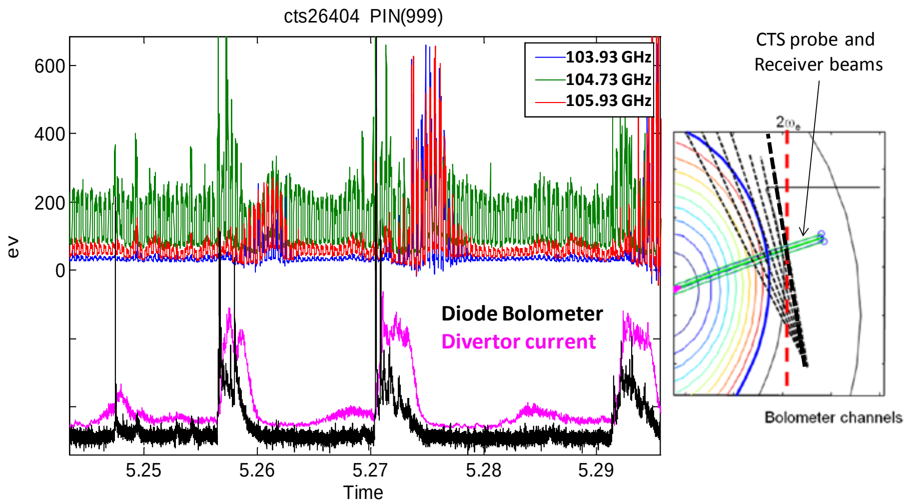

Figure 15. Time traces of three raw CTS channels in the upper panel. The blue and red traces represent channels that correspond to the frequency of the observe narrowband SE (see Figure 14). The green trace is a central channel. The bottom panel shows two traces from the bolometer and divertor current denoted by black and magenta lines respectively. The graph on the right shows the line of sight view of the bolometer channel which is located at the same sector as the CTS antennae.

Figure 15 shows the time behavior of this type of SE which is represented by the blue and red traces. The traces show an increase in intensity with a time delay in the range of 3-4 ms after the ELM crash when the plasma edge pressure drops as shown by the bolometer and divertor current signals. Surprisingly, preliminary analysis has shown that this interesting time delay is not dependant on the ELM frequency suggesting that it is weakly dependant to the ELM size. Unfortunately the fast ion loss detectors (FILD) on AUG were not operational during the CTS experiments. However, FILD has observed regular expulsions of fast ions after an ELM crash where some events also have a time delay of 1-3 ms after the ELM crash. Further analysis and experiments with more edge diagnostics are planned for the upcoming 2012 campaign.

1. E.V. Suvorov et al, Plasma Phys. Control. Fusion **39,** B337 (1997).

2.3.12 Measurement of very large spectral power densities in the lower hybrid range of frequencies at ASDEX Upgrade

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We have measured very large spectral power densities (SPDs) in the frequency ranges of the lower hybrid frequency f_{LH} and its second harmonic at ASDEX Upgrade. Due to their shape in an SPD plot (Figure 16), they have been dubbed ears. Similar spikes in the f_{LH} range have been observed on Wendelstein 7-AS [1], on TEXTOR, and on LHD.

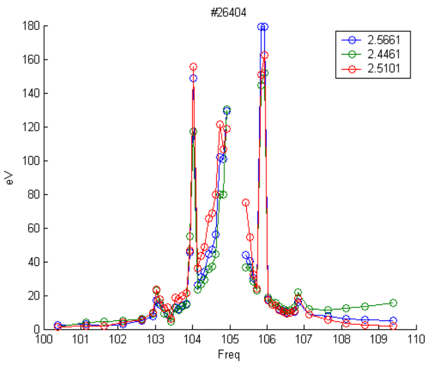

Figure 16. Measurement of very large SPDs at about ±1 GHz frequency shift from the gyrotron frequency f_{gyr} (105 GHz). Typical measurements at 3 different times are shown here. A second set of smaller peaks appears at f_{gyr} ±2 GHz

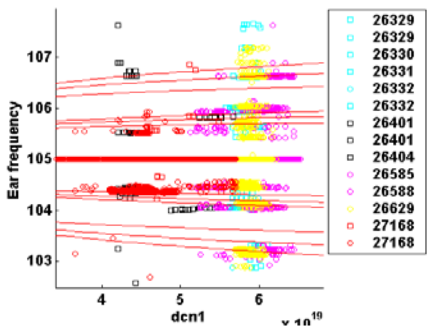

Figure 17. The frequency of the ears is plotted over the central electron density for several discharges. The red lines indicate typical frequency ranges of $f_{gyr} \pm f_{LH}$ and $f_{gyr} \pm 2f_{LH}$.

High resolution measurements have revealed that ears consist of many spikes separated by roughly the ion cyclotron frequency. The appearance of the ears depends on the configuration of the neutral beam injection heating or probing beams: Perpendicular and counter-current injection favours their appearance. If ears appear in CTS measurements at ASDEX Upgrade, their frequency lies usually around ±1 GHz or around ±500-700 MHz away from the gyrotron frequency fgyr (105 GHz), but never simultaneously in these two frequency ranges. We have also observed that a second, outer set of ears can appear at twice the frequency shift of the inner set of ears, if the spectral power density of the inner set of ears is large. In Figure 17 the frequency of the ears is plotted over the measured central electron density at ASDEX Upgrade for several discharges in which ears appeared in the CTS spectra. We also plot $f_{gyr} \pm f_{LH}$ and $f_{gyr} \pm 2f_{LH}$ for magnetic fields corresponding to the low field side edge, the center, and the high field side edge and as function of the density. In particular at the edge the density varies significantly, and so one can usually find a point where f_{LH} matches the observed frequency well. The frequency range in which the ears appear is the same as the expected frequency shift range in which fast ions can be observed at ASDEX Upgrade. The SPD in the ears is often an order of magnitude larger than that expected due to fast ion collective Thomson scattering, sometimes two orders of magnitude. While ears therefore hamper the observation of fast ions, they are an interesting phenomenon by themselves that are yet to be understood. For example, a second set of ears has yet neither been observed nor explained elsewhere.

1. E.V. Suvorov et al., Plasma Phys. Control. Fusion **37**, 1207 (1995).

2.3.13 CTS measurements with fast probe power modulation on ASDEX Upgrade

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On ASDEX upgrade, the effects of ELMs make background subtraction highly challenging with the traditional approach in which the probe power is modulated on/off in a 2 ms on/3 ms off duty cycle. Increasing the modulation frequency by a factor of 10 enables accurate background subtraction by resolving the background fluctuations due to ELMs in time. However, this mode of operation is challenging from a technical perspective and with respect to interpretation because the gyrotron supplying the probe power cannot be turned completely off when operating at such high modulation frequencies. New procedures and analysis software were therefore developed in 2010 for operation of the CTS diagnostic at ASDEX Upgrade with rapidly modulated probe power and results of initial trials with this new technique were reported in the 2010 annual report. In 2011 these test were continued and it was found that this new mode of operation fully meets expectations and enables highly accurate background subtraction which significantly reduces an important source of uncertainty for CTS measurements at ASDEX Upgrade. In addition, hardware for a new gyrotron triggering system has been installed and tested to enable greater flexibility when designing experiments with rapid probe power modulation. Previously, only a single series of gyrotron pulses with rapid modulation could be fired in a single plasma discharge, but the new triggering system removes this limitation and thus allows greater freedom in the design of pulse shapes.

In a related development, the trials conducted with rapid probe power modulation indicated that this mode of gyrotron operation may eliminate or drastically reduce interference between the gyrotron and the neutral beam power supply. The off-axis neutral beam injectors (NBI2) and the gyrotrons share the same high-voltage power supply. Previously, it had been found that the on/off modulation of the gyrotron could cause the NBI2 power supplies to fail which prevented operation of NBI2 during CTS measurements. This was unfortunate both from a scientific point of view and because operation with NBI2 had previously been found to significantly reduce the level of secondary emission in the CTS signal. However, during rapid probe power modulation the gyrotron is never turned completely off, and though further tests are required this is expected to enable simultaneous operation of the CTS diagnostic and NBI2.

During 2011 operation with rapid probe power modulation has thus become routine and it may well become the standard operating scenario for the CTS diagnostic at ASDEX Upgrade.

2.3.14 Overview of ASDEX Upgrade CTS hardware upgrades

F. Meo, F. Leipold, S.B. Korsholm, V. Furtula, P.K. Michelsen, D. Moseev, M. Salewski, M. Stejner, S.K. Nielsen and the ECRH team at ASDEX Upgrade (*IPP Garching (D))*
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The original CTS on AUG [1] consists of a receiver coupled to the gyrotron transmission line by a movable intercepting mirror inside the gyrotron's matching optics unit (MOU) box located in the gyrotron hall. The CTS system formerly installed at TEXTOR has been adapted and installed in the AUG NBI control room as the second CTS receiver, as it is illustrated in Figure 18. It is planned that all the CTS diagnostic hardware will be relocated to this room in 2013.

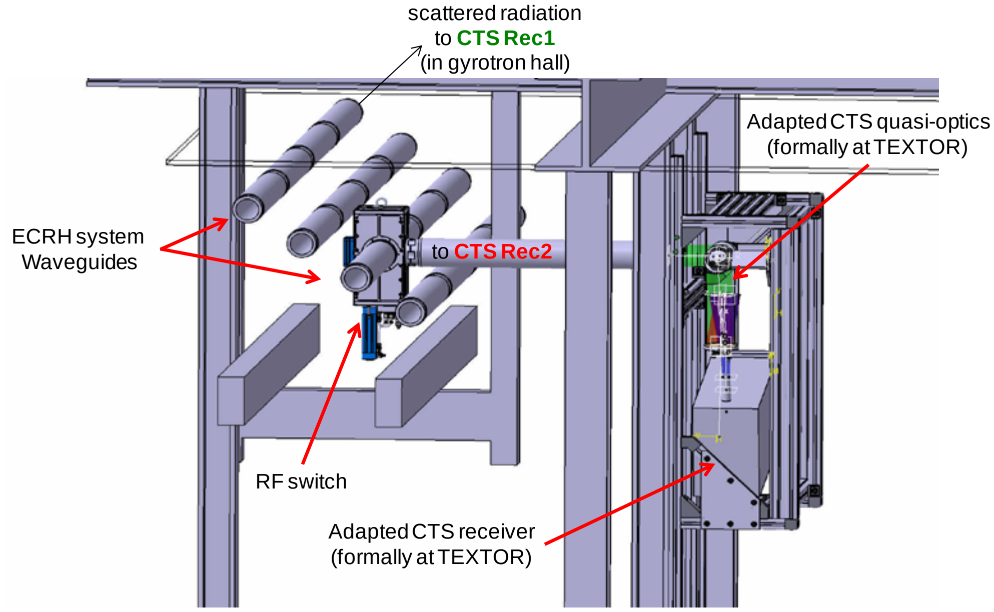
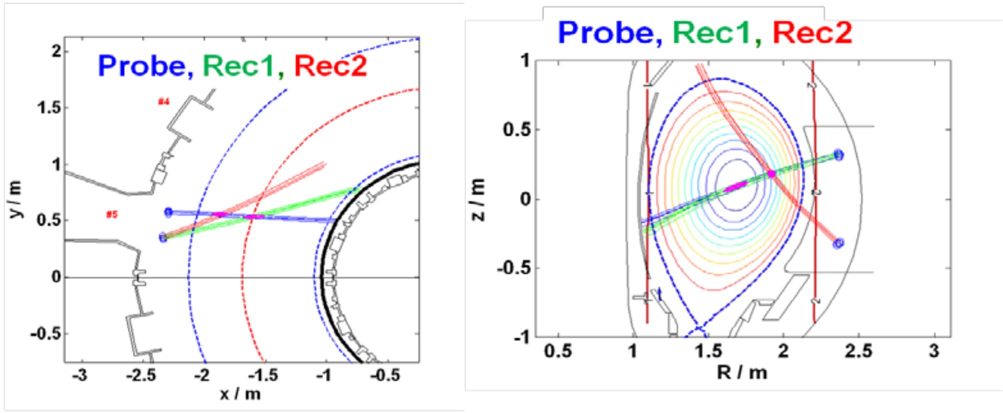


Figure 18. Setup of the RF-switch based 2nd CTS receiver located in the NBI control room. Details of the installation can be found in section 2.3.15.

This new CTS system directly couples to the ECRH waveguides via RF switches designed and constructed in 2011 by Risø DTU. This upgrade will not only give the capability of two simultaneous measurements, it will also have the added flexibility to easily change the receiver transmission line allowing different scattering geometries as shown in Figure 19. The alignment of the system was achieved by using a microwave scanner which not only can measure the beam peak position; it can also detect problems in the beam quality such as side-lobes and astigmatism. Figure 21 in Section 2.3.15 shows an example of the beam pattern after alignment where the red-dashed cross hairs represent the laser reference. The piece-wise alignment technique used on this system is described in more detail in [1]. The alignment and beam quality experiments were also carried out inside the AUG vacuum vessel by using this microwave scanning system and a high precision calibrated arm supplied and operated by the ASDEX Upgrade staff, measuring the global coordinate positions of the measured beams. More details of the in-vessel alignment procedure can be found in [1]. The results show good beam quality and angle discrepancies between measurements and the expected values to within 1 – 1.5° depending on the antenna settings.



(a) (b)

Figure 19. Scattering geometries for the CTS at ASDEX Upgrade, (a) top view (b) poloidal projection. Blue depicts the gyrotron beam, green and red depicts the beams for each receiver as depicted in Figure 18.

Originally purchased for plasma composition measurements, a 5 GHz bandwidth acquisition card was coupled to the first CTS system enabling measurements of both simultaneously. This will allow high frequency resolution measurements of certain portions of the CTS spectra for studies of secondary emission. Improvements to the fast card's acquisition capabilities have been implemented and its exploitation will be carried out in 2012 campaign which will supply key physics information on the SE. Details on the system and the calibration can be found in Section 2.3.16.

As part of the collaboration with IPP, it is important to make the CTS compatible to other microwave diagnostics on ASDEX Upgrade. In CTS experiments, powerful radiation is launched into a non-absorbing plasma i.e. magnetic field and probing radiation frequency is set such that the electron resonances layers lie outside the plasma. Hence to protect the electron cyclotron emission (ECE) diagnostic which measure electron temperature, a 105 GHz based notch filter has been designed and constructed by Risø DTU. The notch filter was tuned and installed in 2011 which will enable the use of the ECE during CTS experiments for 2012 campaign. Details are described in Section 2.3.18.

1. F. Meo et al, Rev. Sci. Instrum. **79**, 10E501 (2008)

2.3.15 Installation of a second CTS receiver at ASDEX Upgrade

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A second CTS receiver (formerly used at TEXTOR) has been reconfigured for installation at ASDEX Upgrade (see also Section 2.3.14). The receiver was designed, built, and tested at Risø DTU. The installation took place in the autumn of 2011. The layout of the system can be seen in Figure 18 above. Figure 20 shows the installed receiver and waveguide switch in the NBI control room at ASDEX Upgrade. The receiver is fed with a signal coming from an existing gyrotron transmission line. The required switch, which can switch the transmission between the gyrotron and the receiver, was also designed, built, and tested at Risø DTU.

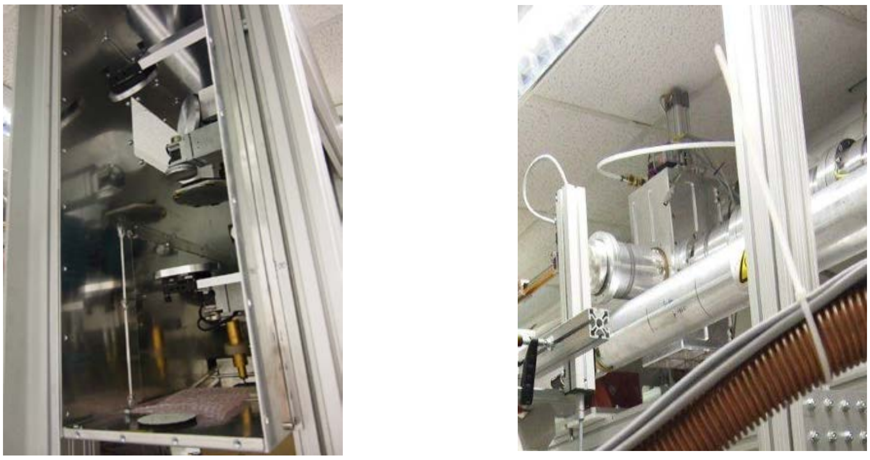

Figure 20. Photographs of the installed receiver box (left) and the RF switch installed in transmission line (right).

The quality of the newly designed quasi-optical transmission line has been verified by attaching a microwave source to the receiver horn antenna and measuring the spatially resolved beam pattern at the transition point to the waveguide. The transition point defines the point where the signal leaves the waveguide and propagates in free space quasi-optically. The beam pattern is depicted in Figure 21.

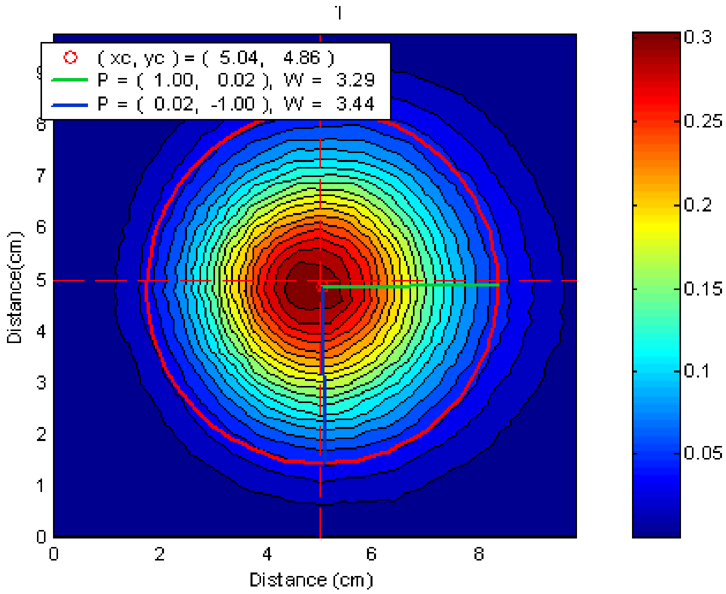

Figure 21. Spatially resolved beam pattern at the transmission point of the quasi optical transmission line and the waveguide.

The spatial beam profile can be described by a Gaussian beam according to the design. The two polarizer plates in the quasi-optical transmission line were originally designed to serve as a lambda/2 and a lambda/4 plate at 110 GHz, respectively. This is not valid anymore for the new operation frequency of 105 GHz. The polarizer has been characterized using a 2-channel heterodyne detector capable of measuring elliptically circularly polarized light. Based on these measurements a code was developed to calculate the polarizer setting in order to convert the generally elliptically polarized light to linearly polarized light required for the receiver. The described installation will allow future use of two independent receivers for CTS, simultaneously.

2.3.16 Installation and initial commissioning activities of a fast acquisition system for CTS on ASDEX Upgrade

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Plasma composition measurements by CTS rely on the ability to resolve the ion cyclotron structures in CTS spectra with $\Phi=\angle(k^{\delta}, B) \cong 90°$. This in turn requires a frequency resolution around 1 MHz in the measured spectrum which is achieved through direct digitization and Fourier analysis of the CTS signal. In the past such measurements were done with oscilloscopes, but this type of receiver setup is cumbersome and time consuming to work with and the available memory restricted the possible integration time to 25 ms. In order to build a permanent and more capable setup for plasma composition measurements on ASDEX Upgrade a new digitizer was therefore purchased from National Instruments: the NI PXIe 5186 8-bit digitizer which provides sampling rates up to 12.5 GS/s, analogue bandwidth of 5 GHz and a memory of 1 GB allowing integration times in the 100 ms range. This was delivered in early 2011 and has since been integrated in one of the two CTS receivers at ASDEX Upgrade along with the required secondary mixing stage. Additionally, work has been undertaken to develop and test operating procedures and software for this setup. Much of this work was focused on the development of procedures and software for calibration of the new receiver setup. In past experiments at TEXTOR calibration was performed by measurements of black-body radiation from optically thick resonances in the plasma. On ASDEX Upgrade this procedure would be impossible or very expensive, so an alternative approach was required. Procedures have therefore been developed to calibrate the system by detecting the different signal levels in radiation from two black body sources kept at room temperature and cooled with liquid nitrogen, respectively. This procedure is routinely used to calibrate the standard CTS receiver setup used in fast-ion measurements, and can be performed independently requiring no special plasma operations. However, it is more challenging to perform with the new setup for measurements with high frequency resolution due to the limited bit resolution of the digitizer, and some work was required to develop at suitable setup with sufficient amplification and signal-to-noise ratio. Initial trial with this system have so far successfully detected the different signal levels, and it is expected that this procedure will enable routine accurate calibration of the system for the coming campaign on ASDEX Upgrade. Figure 22 shows an example of a calibration curve obtained in initial trials with this procedure. In this example the noise level is still too high, but this can be reduced by increasing the integration time to obtain a more accurate calibration.

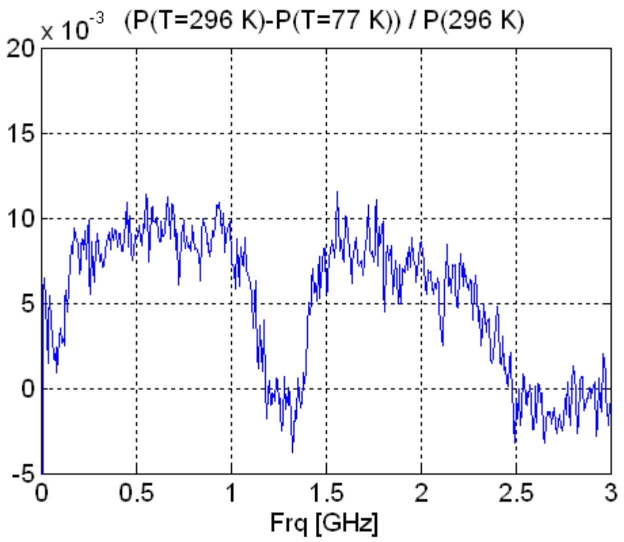

Figure 22. A calibration curve obtained for the new high resolution receiver setup at ASDEX Upgrade for plasma composition measurements. This trial calibration demonstrates the feasibility of calibrating the system by measurements of black-body radiation from sources at room temperature and cooled with liquid nitrogen. However the noise level could be reduced by increasing the integration time for more accurate calibration.

During the early part of the 2011 ASDEX campaign the new receiver setup was tested and contributed as a piggy-back experiment on the standard CTS experiments discussed elsewhere. At this time a calibration was not yet available, but new setup did enable certain components of the secondary emission seen at ASDEX Upgrade to be resolved in greater detail than previously possible and detected discrete peaks within these signals. An example of such measurements with the fast digitizer is shown in Figure 23.

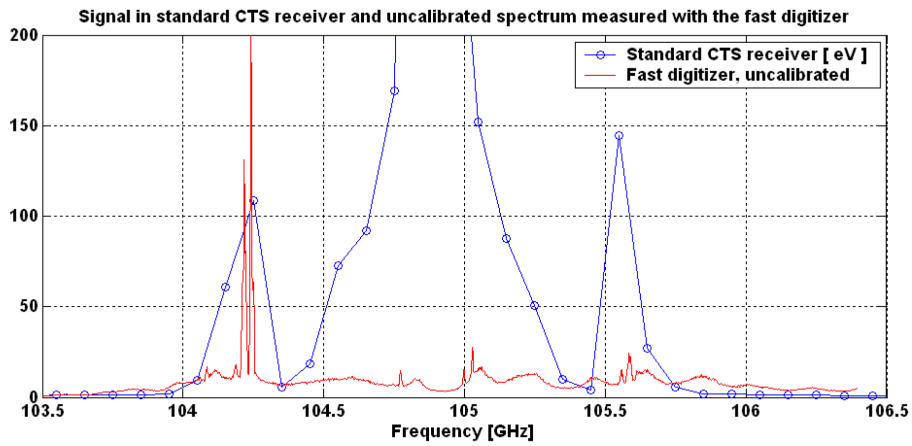

Figure 23. A comparison of measurements with the standard CTS receiver setup used for fast-ion measurements and uncalibrated measurements with the new setup for high-resolution measurements. The secondary emission was seen right after the neutral beam injector was turned on as broad peaks at frequencies around 104.3 and 105.6 GHz. With the new digitizer these peaks can be resolved in detail and are found to consist of several discrete peaks with frequency intervals around 23 MHz (i.e. in the ion cyclotron range of frequencies for these plasmas).

The first dedicated experiments with the new receiver setup were planned and prepared for the end of July 2011. At this time, at the end of the 2011 ASDEX Upgrade campaign, it would be possible to operate with plasmas containing hydrogen, deuterium and helium instead of the usual pure deuterium plasmas used at ASDEX Upgrade. Since the experiments were aimed at plasma composition measurements this phase of the ASDEX Upgrade experimental schedule therefore provided the most interesting plasmas. Specifically, experiments had been prepared to test a range of scattering geometries with $\Phi=\angle(k^{\delta}, B) \cong 90°$ in order to demonstrate the ability to detect ion cyclotron structures in CTS spectra at ASDEX Upgrade and find the optimal scattering geometry for subsequent experiments. However, due to a combination of strong demand for discharges on ASDEX Upgrade at this time and an accident with one of the CTS mirrors which caused a misalignment of the system the experiments could not be carried out and had to be postponed until the 2012 campaign on ASDEX Upgrade. The first results from the new receiver setup are therefore expected in April 2012.

2.3.17 Usability of a two mirror system for detection and launching of gyrotron power for NTM stabilization

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The idea of NTM tracking and control using two mirrors, one for tracking (receiver) and the other for control (launcher) is that both mirrors are controlled in parallel. While one mirror can detect an NTM during scanning, the other mirror is always in a position where gyrotron power can be launched into the NTM for stabilization. The receiver currently used for collective Thomson scattering with a modified front-end for 140 GHz is used as a radiometer for detection. Due to the geometric design of the mirror steering system, driving both mirrors exactly parallel is not a precise solution, since the port plug design does not follow the curvature of the plasma.

Each mirror can be tilted from 3° to 53° poloidally and rotated from -30° to + 30°. These angles are referred to as *machine angles*: alpha and beta, respectively). Since launching and receiving beams are parallel if the set of machine angles are identical for both mirrors, the two beams intersect the plasma boundary surface into the plasma under different angles. These angles are referred to as beam intersection angles. The beam intersection angles are defined as the angle between the beam and the horizontal plane (elevation) and the angle rotated away from the radial position (rotation). If the objective is that the receiving beam and launching beam shall intersect the plasma under the same beam intersection angles, the machine angles for the individual mirrors must be different.

The mirrors cannot be scanned in an arbitrary trajectory in the machine angle space in order to ensure identical beam intersection angles. Rather than, only the machine angle alpha can be scanned during a discharge. Consequently, it is not possible to scan two mirrors and maintain the same set of beam intersection angles for both mirrors.

In order to investigate the feasibility of a 2-mirror system for tracking and eliminating NTMs, the following assumptions are made:

i) Prior to the scan, the initial machine angles (alpha and beta) are determined beforehand depending of the NTM stabilization scenario and can be different for receiving and launching beam.

ii) The scan changes the machine angle alpha by the same amount for both mirrors

iii) The difference in beam intersection angles (elevation and rotation) between both beams shall be within 1 degree.

This is explained on the following example: The axes in Figure 24 represent the machine angles for the launching beam (alpha [5…53], beta [-30…30]). The machine angles for the receiver beam have an offset of +1 for alpha and -3 for beta (the angles are randomly chosen): (alpha [6…54], beta [-33…27]). The beam intersection angles for launching and receiving beams are calculated for each set of machine angles and the difference between the beam intersection angles for both beams are calculated.

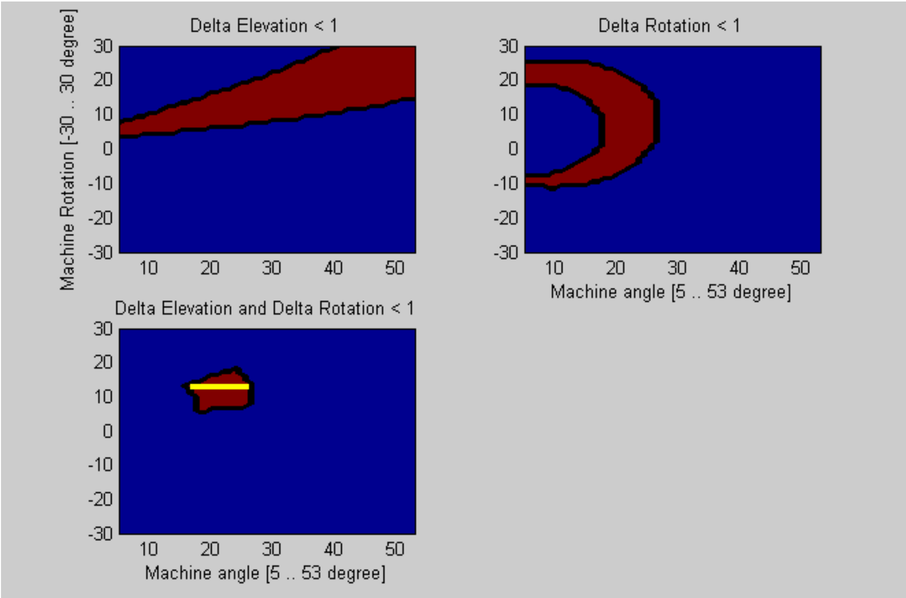

Figure 24. See text for further description. The red areas in the contours represent a difference in elevation (upper left panel) and rotation (upper right panel) of less than 1 degree. The red area in the contour plot in the lower left panel depicts where the difference in elevation and rotation are simultaneously less than 1 degree. The yellow line depicts a scanning scenario.

The red area in the upper left panel in Figure 24 represents all positions for the launching beam, where the difference between launching beam elevation and receiver beam elevation is less than 1°. The red area in the upper right panel in Figure 24 represents all positions for the launching beam, where the difference between launching beam rotation and receiver beam rotation is less than 1°. The combination of these two graphs is shown in the lower left panel of Figure 24. When operating the launching beam within the red area, both, the elevation angles and the rotation angles of both beams are within 1°. The yellow line in the lower left panel in Figure 24 depicts a possible scan, since the scanning can only be performed by changing the machine angle alpha. When beta is set to 14° for the launching mirror and beta for the receiving mirror is set to 11°, alpha can be scanned from approximately 15° to 25° for the launching beam while, at the same time, alpha for the receiving beam is scanned from 16° to 26°. This scan ensures that the beam intersection angles are always within 1°.

By changing the offset angles for the receiver beam, the whole machine angle space can be covered.

2.3.18 105 GHz notch filter for ECE

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A main component in the CTS receivers is the notch filter, which prevents stray radiation from the gyrotron to overload or even destroy the receiver mixer and amplifiers. The typical notch filter has a rejection band of a few hundred MHz and a pass band of some 10 GHz. Due to the success with making notch filters for the CTS system, a 140 GHz notch filter was earlier produced for the ASDEX ECE group in order to prevent gyrotron radiation disturbing the ECE systems. The requirements for ECE notch filters are somewhat different, because both the rejection band and the pass band need to have wider bandwidth. During 2011 a notch filter with rejection bandwidth of 1 GHz centered at 105 GHz has been designed and tested, see Figure 25. The pass band coverage is larger than 30 GHz which is more than recorded earlier for fusion plasma diagnostics. This was made possible by using the dominant TE_{111} mode. The design is based on a rectangular waveguide with 8 cylindrical cavities coupled by T-junction apertures formed as thin slits. The cavity diameter is 2.1 mm and the length is approximately 2.4 mm, but can be adjusted by tuning screws. The performance of the constructed filter is measured using a vector network analyzer. The distance between the resonators is similar to the other filters $5\lambda_g/4$, where λ_g is the guide wavelength. The resonators have a Q factor of approximately 3500 which makes the filter sufficiently broad in the rejection bandwidth to protect the ECE receiver from the stray radiation. The ratio between the reflected and the transmitted power measured in dB i.e. the S-parameter, $S_{21,}$ is shown in Figure 25. The left graph presents insertion loss (S_{21}) measurements centered on the notch, while the right graph presents the insertion loss for a frequency range where ECE radiation is expected.

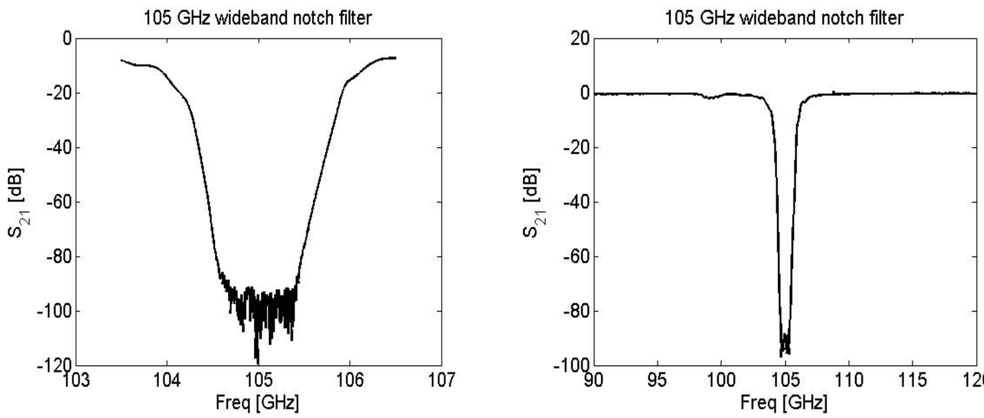

Figure 25. A notch filter with wide rejection made for the ECE group at ASDEX Upgrade. This filter will protect the ECE receiver during piggy-back experiments where the CTS group is also participating.

2.3.19 Tomography of fast-ion velocity-space distributions from synthetic fast-ion diagnostics

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The tokamak ASDEX Upgrade is equipped with collective Thomson scattering (CTS) and fast-ion D_α (FIDA) diagnostics and thus has unique possibilities to study fast ion distribution functions in plasmas. Both diagnostics measure fast ions in small volumes compared with the plasma size. In either diagnostic one pre-selects a projection direction through geometric arrangement of the experiment and measures a 1D function of the full fast-ion 2D velocity-space distribution function. One new CTS receiver and one new FIDA optical head have been installed at ASDEX Upgrade in 2012 such that two CTS receivers as well as two FIDA receivers are now available. The new measurement options open up the possibility of computing tomographies of two-dimensional fast ion velocity distribution functions. In initial studies, our tomographies are reconstructed from localized synthetic CTS or FIDA measurements on 2D fast-ion distribution functions computed with TRANSP (Figure 26). Two approaches to reconstruct the target function have been taken, both of which exploit recently developed weight functions which relate the CTS or FIDA measurements to 2D fast-ion velocity distribution functions [1-3]. In the first we build a transfer matrix *A* which takes the target 2D fast-ion distribution function into a set of synthetic measurements and find its Moore-Penrose pseudo-inverse or generalized inverse. In the second approach we iterate to the solution by comparison of the target synthetic measurement and the iterated synthetic measurement. The concept of weight functions allows the derivation of an intrinsically tractable reconstruction prescription that was not possible in previously published work [4]. Applying our prescription to a set of real 1D fast-ion measurements will yield an entirely experimentally determined 2D fast-ion velocity distribution function.

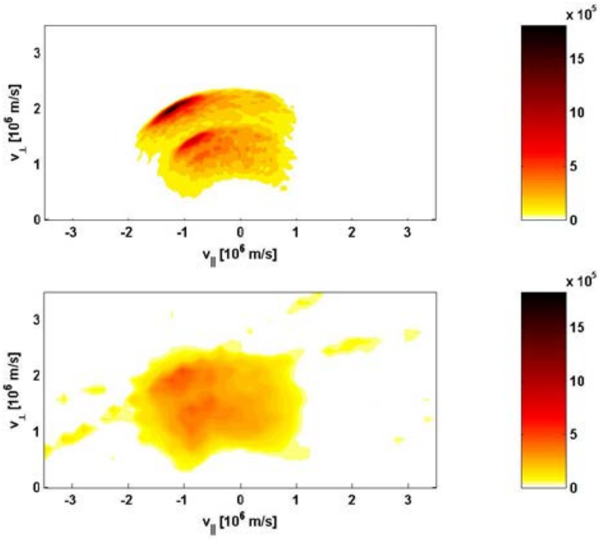

Figure 26. Tomography of a realistic beam ion distribution function at ASDEX Upgrade from four simultaneous synthetic CTS measurements. Information that would be experimental inaccessible due to scattering from bulk ions has not been used.

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3 Fusion Technology

3.1 Cost of capacity model of TF coils based on coated conductors

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Summary: The objective of this work being a part of WP11-DAS-HTS-02-01/Risø/BS is to formulate a model, which can describe the relation between the cost of the superconducting TF coils based on coated conductors of a future fusion power plant and the power produced by the plant. One can thereby roughly estimate the superconductor Cost Of Capacity (CoC) as the ratio between the cost of the coated conductors needed for the TF coils divided by the rated power of the fusion power plant. A simple analytical model resulted in *CoC* = 13 MEuro/MW for TF coils based on the Superpower tape operated at *T* = 50 K and with *I* = 20 A in a maximum magnetic field of 13.4 Tesla. A finite element model of elliptical TF coils resulted in a *CoC* = 15 MEuro/MW being the same order of magnitude. It is concluded that *T* = 50 K operation will be challenging, but lowering the operation temperature to *T* ~ 25 K would probably make it possible to introduce the technology. Thus it is recommended to consider a combination of coated conductor based TF coils and a liquid neon *T* = 27 K cooling system in the design of future fusion power plants.

The simplest description of a magnetic field resembling a fusion power plant is obtained by considering a circular torus illustrated in Figure 27. The magnetic field B_φ along the center circle spanned by *R* will simply be given by

$$B_\varphi = \frac{\mu_0 LI}{4\pi^2 Rr} \qquad (1)$$

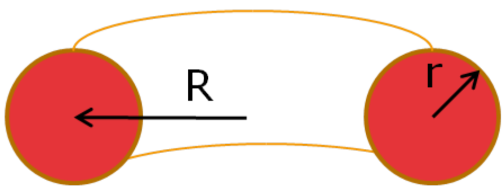

Figure 27. Illustration of a simple torus with major radius R and minor radius r.

This magnetic field provides the confinement of the plasma in a fusion power plant and the fusion power density P_{DT} of Deuterium-Tritium burning plasma is approximately given by

$$PDT = 4.3\left[\frac{\beta^2 B_0^4}{\left(1+\frac{T_e}{T_i}\right)^2}\right]\left[\frac{MW}{m^3}\right] \qquad (2)$$

where β is the ratio between the plasma thermal energy density and magnetic energy density, B0 is the local magnetic flux density, Te and Ti are the temperature of the

electrons and ions of the plasma respectively [2]. The β-ratio is a constant related to the density n of the burning plasma.
Now the power production P in the torus can be estimated by assuming that the magnetic flux density is given by eq. (1) in a plasma extending to a fraction of the minor torus radius, $r_{plasma} = \alpha r$

$$P = P_{DT} V_{plasma} = P_{DT} \cdot \pi r_{plasma}^2 \cdot 2\pi R \tag{3}$$

The cost C of the coated conductors needed to realize the magnetic flux density of eq. (1) is simply evaluated from a unit price cost per meter and the total length L of tape needed

$$C = Unitprice \cdot L \tag{4}$$

Now the Cost of Capacity (CoC) of the fusion torus is determined by the ratio between the superconductor cost C and the power production P

$$CoC = \frac{C}{P} = \frac{128\pi^7 \left(1 + \frac{T_i}{T_e}\right)^2}{4.3\mu_0^4 \beta^2} \frac{Unitprice}{L^3 I^4} \frac{R^3 r^2}{\alpha^2} \tag{5}$$

Here T_i and T_e are the temperature of the electrons and ions in the plasma, μ_0 is the vacuum permeability, β is the ratio between the thermal energy of the plasma and the magnetic energy density, *UnitPrice* is the price of the coated conductor per meter, L is the total length of coated conductor wound on the torus, I is the current in the coated conductor, R and r are the major and minor radius of the torus and α is the fraction of the minor radius where the plasma exceeds to.

Magnetization measurements of the hysteretic behavior of a square piece of coated conductor tape with the applied field along the tape normal have been used to estimate a scaling factor of the critical current I_C as function of temperature and magnetic fields [3]. The specification of a future fusion power plant has been given in the Power Plant Conceptual Study report (PPCS) and here the most advanced scenario termed D will be used to discuss the needed amount of coated conductor and also the expected Cost of Capacity [4].
The minor radius r is approximated by setting an elliptical cross section equal to the area of a circle, $\pi a_{TF} b_{TF} = \pi r^2$, giving $r = \sqrt{a_{TF} b_{TF}} = 4.9\ m$. The scaling factor of the critical current is 0.2 at T = 50 K and B = 13.4 Tesla [3]. The corresponding critical current of the Superpower tape is then I_C(50K, 13.4 Tesla) ~ 125 A·0.2 = 25 A. By implementing a safety margin by operating at 80 % of I_C one would come to an operation current of the order I_{TF} = 20 A. The total length of coated conductor needed to realize the TF magnetic flux density will be

$$L = \frac{4\pi^2 R r B_\varphi}{\mu_0 I_{TF}} = \frac{4\pi^2 6.1 m \cdot 4.9 m \cdot 5.6 T}{4\pi \cdot 10^{-7} Hm^{-1} \cdot 20 A} = 2.63 \cdot 10^8 m = 263000\ km \tag{6}$$

where $R=6.1\ m$ and $r=4.9\ m$ are the major and minor radius respectively, B_φ is the field on the axis, μ_0 is the vacuum permeability and I_{TF} is the current in the coated conductors in the TF coils.

With current prices of 4 mm wide coated conductors being at the level of *UnitPrice* = 24 Euro per meter then the total cost of the TF coils can be estimated to be

$$C = Unitprice \cdot L = 6.3 \cdot 10^{9}\, Euro \qquad (7)$$

which should be compared to the expected price of ITER estimated to be 13 billion Euro and including expenses to 80000 km of Nb_3Sn wire. Thus the coated conductor is comparable to the Nb_3Sn wire, but it is more expensive. A big question is however the saved operation cost due to an operation temperature of T = 50 K of the fusion power plant.

Some assumptions must be made before the Cost of Capacity can be calculated using eq.(5). First it is assumed that the temperature of the electrons and ions are the same, $T_e = T_i$. Secondly the β-ratio must be limited below 5 % in order to have a stable plasma and if β = 0.026 is assumed then the power production becomes P = 2.5 GW in agreement with [4]. Finally the wall thickness is estimate from the PPCS to result in an approximately, $\alpha \sim 0.55$. Inserting the numbers above one obtains the following estimate

$$\begin{aligned} CoC = \frac{C}{P} &= \frac{128\pi^7\left(1+\frac{T_i}{T_e}\right)^2}{4.3\mu_0^4\beta^2}\frac{Unitprice}{L^3I^4}\frac{R^3r^2}{\alpha^2} \\ &= \frac{128\pi^7}{4.3\mu_0^4 0.026^2}\frac{24Euro/m}{\left(2.63\cdot10^8 m\right)^3\left(20A\right)^4}\frac{\left(6.1m\right)^3\left(4.9m\right)^2}{0.55^2} \qquad (8) \\ &= 7.9 MEuro/MW \end{aligned}$$

One would have to divide this number with the expected efficiency of the fusion power plant defined as the ratio between the fusion power production and the power needed to heat the plasma using auxiliary current drives. This efficiency is expected to be 0.6, whereby the *CoC* will get to the order of 13 MEuro/MW.

Figure 2 is showing a COMSOL finite element model calculation of the magnetic field distribution of a TF coil based on coated conductors when the current density is assumed to be J_{coil} = 27 A/mm^2 corresponding to I_{TF} = 14.5 A. A CoC = 15 MEuro/MW is obtained in that case being the same order of magnitude as the analytical model result.

Discussion:

A Cost of Capacity (*COC*) of the order 13-15 MEuro/MW is obtained by using the current price and properties of coated conductors operated at T = 50 K. These numbers must be compared with expected cost of capacity of other renewable sources such as wind and solar power, which is expected to become of the order 1 MEuro/MW within the next decade. However the *CoC* of eq. (8) only includes the bare coated conductor cost and will eventually also have to include all other costs.

Thus the simple estimates of the Cost of Capacity indicate that the coated conductor solution seems very expensive and cost reduction guide lines will be needed. From the analytical model one can provide the following suggestions:

1) **Reduce the *UnitPrice* by a factor of 10.**
2) **Increase the operation current I_{TF}.**
3) **Decrease operation temperature.**

Superpower has stated that scenario 1) is not likely, but that 2) is expected [5]. Finally lowering the operation temperature to T = 25 K would give an increase of I_C in the order of a factor 4-5 [3].

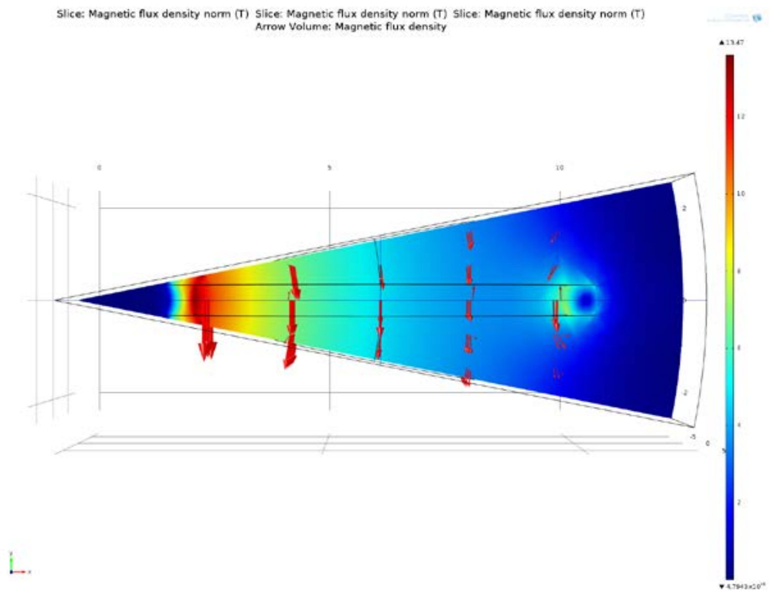

Figure 28. Magnetic flux density of TF coil when ITF = 14.5 A (Jcoil = 27 A/mm2) resulting in a value of B ~ 13.5 T on the conductors, but a center flux density of 4.9 T being lower than the power plant Scenario D with 5.6 T [1]. The Cost of Capacity of the coated conductor TF coils is estimated to be 15 MEuro/MW.

Conclusion: A simple analytical model of the superconductor contribution to the Cost of Capacity based in an circular torus shaped fusion power plant has been proposed and an estimate in the order of 13 MEuro/MW has been obtained using current properties of a coated conductor from Superpower operating at T = 50 K. Based on the Cost of Capacity model it is suggested that a *CoC* reduction of a factor 10 might be obtained from improved critical current I_C of the coated conductors combined with a lowering of the operation temperature into the region of T = 25 K. Thus a combination of a coated conductor cable concept and liquid neon is suggested as one possible starting point of further investigation of the feasibility of using high temperature superconductors in future fusion power plants.

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4 DTU Contribution to EFDA-TIMES

4.1 Modelling fusion in the energy system

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Within the Socio-Economic Research on Fusion (SERF) programme EFDA and the Associations are developing a multi-region global long-term energy modelling framework (EFDA-TIMES), which has been developed together with similar models, which are used by the International Energy Agency (IEA), the US Department of Energy and several project under the European Union 6th and 7th Framework Programmes.

The technologies are organised into a network of energy flows linking demand and supply. Forecasts of energy demands in the various sectors come from global economic models. The energy system in these models is optimised by minimising total system costs subject to constraints reflecting infrastructure, technology availability and policy objectives, e.g. reduction of CO_2 and other greenhouse gasses. In these models the energy system is divided into the following main sectors: Upstream, Electricity, Industry, Residential, and Transport.

Figure 29 illustrates typical results from the EFDA-TIMES model. Electricity is generated by an optimal set of technologies, which are balanced by the selection of fuel prices, technology costs and constraints on resources and technology development. Fusion units will operate very similar to current large-scale thermal generating units for supply of industrialised regions and population centres, which now dominate electricity generation. New technologies will become significant earlier than fusion. Some of them are small-scale technologies located much closer to the consumers. Others are dependent on natural resources located in coastal regions with shallow water or deserts. The potential of these resources is huge by 2050, when fusion may become available, but their production varies with sun and wind, and they require very large investment in long-distance transmission to population centres. All these technologies will reduce the market share of large-scale thermal units, which includes fusion.

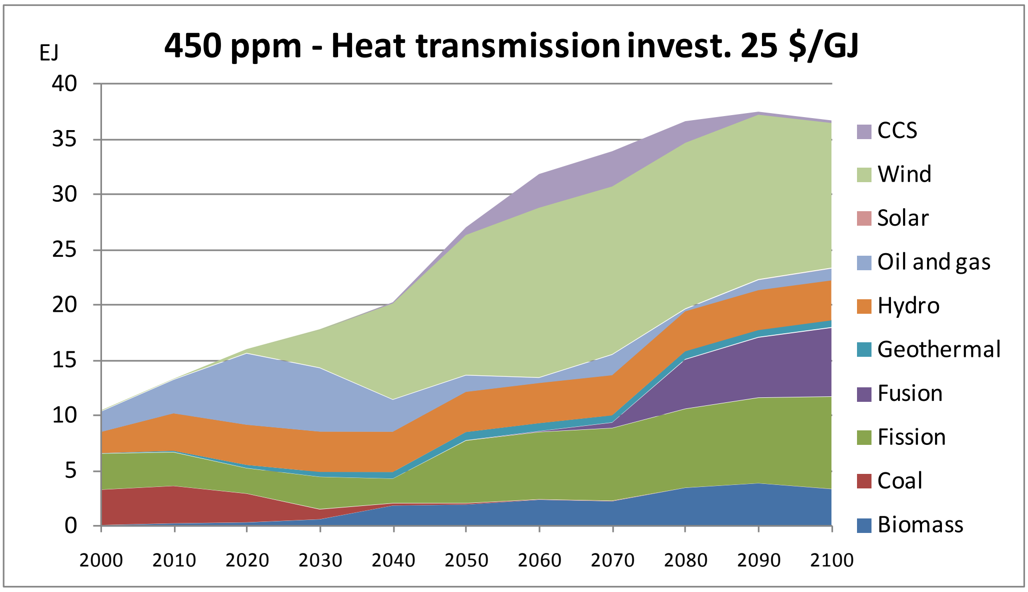

Figure 29. EFDA-TIMES model result for electricity generation in Europe 2000-2100. assuming CO2 emissions constrained at 450 ppm from 2050, maximum fission generation 25 % from 2030 and aggregated average investment in heat transmission for large-scale urban district heating at 25$ per GJ annual flow [2].

The EFDA-TIMES model is a global model currently divided into 15 regions base year 2000 from IEA statistics and the time horizon year 2100. The ongoing development aims at revising the number of regions, update of starting year and enhancement of the description of technologies that are competing with fusion, in particular variable renewable and nuclear fission.

Contributions to EFDA-TIMES from the Systems Analysis Division (from 2012 part of the new institute DTU Management Engineering) are co-ordinated within the work on other TIMES-based models on the global and European level and contributions to the IEA Implementing Agreement ETSAP (Energy Technology Systems Analysis Programme) [1,3]. These activities also include 2-3 PhD students.

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5 Industry awareness activities towards ITER

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Following the ITER site decision on June 28th 2005, Risø DTU was the main driver in the launch of activities to inspire Danish companies and make them aware of the possibilities of being a supplier to the construction of ITER as described in some detail in [1]. This effort originally initiated in 2005 was further developed and maintained in 2006-2010. In 2010 a main achievement was the successful setting up and initiation of the Big Science Secretariat which is described in Section 5.1 below.

The Danish representative of the F4E-ILO network is Søren B. Korsholm of Association EURATOM -DTU. The network now comprises 17 European ILOs. During 2011 the tasks and procurements from the ITER Organisation (IO) and F4E have received some attention from Danish companies, and a number of bids and expression of interests have been placed during 2011 – still so far without success. The opportunities for participation in procurements and events are announced via the newsletter of the Big Science Secretariat.

5.1 The Big Science Secretariat – Denmark

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With offset in the Risø DTU initiative on promoting the ITER industrial opportunities to Danish companies, a partnership was made between Risø DTU, FORCE Technology, and Teknologisk Institut (TI – Danish Technological Institute) – both are non-profit technology service institutes. The aim of the partnership was to create a unit and a project which aims at increasing the Danish industrial involvement in the construction of (European) big science facilities. The project is called Big Science Sekretariatet in 'Danish' or The Big Science Secretariat – Denmark (BSS).

Supported by the Confederation of Danish Industry and twelve Danish companies (with sizes in the range 5 to 15.000 employees) the partners applied for funds from the national Council for Technology and Innovation (RTI) and 3.6 million DKK was granted in late 2009. Simultaneously another part of Teknologisk Institut had been granted a similar sum for a related project from RTI and it was requested that the two projects were merged. This was successfully achieved during 2010 and the final signature on the BSS project was made in August 2010. BSS now has a total budget of 11.4 mio. DKK out of which 7.2 mio. DKK comes from RTI. The time span of the project is until the end of 2012. The project was lead and coordinated by Risø DTU – from 2012 the project is lead and coordinated by DTU Physics.

The aim of the BSS initiative is two-fold: to increase the awareness of Danish companies on the potential for commercial participation in the construction phase of big science projects, and to assist companies in the required competence and network building phase prior to being able to bid for contracts on ITER, ESS, CERN, XFEL, ESO etc. At the same time, BSS is connecting to the big science facilities to make the Danish company competences known to them. To facilitate this better BSS partners are now taking care of the ILO roles at F4E/ITER, ESO, CERN, and ESRF.

The pivot of the BSS project is the BSS secretariat (from 2012 located at DTU Physics) which is managed by a full time professional. In addition, a number of experts at DTU, FORCE, and TI are connected to BSS, in order to assist Danish companies in their need for competence building and expert advice in the preparation phase. A number of awareness activities were conducted in 2011, where the main event was the Danish Big Science Industry Day 2011 with more than 100 participants and 12 high level representatives from F4E, CERN, ESS, and ESO. The project has received positive attention and remarks from Danish companies as well as several of the European big science facilities. The BSS project has also received quite some attention by the Danish press (approximately 39 articles in 12 months), and other European countries are considering to make similar initiatives. A main source of news from BSS to the 50+ members and about 100 additional subscribers is the weekly BSS newsletter with news, events announcements, and lists with current tenders.

The project is further described in the BSS webpages www.bigscience.dk.

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6 Public information in Denmark

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The public information activities in the Danish fusion association comprise a broad range of activities from press contact and assisting students to talks about fusion at different venues. A major part of the activities is the performances of the Fusion and Plasma Roadshow, described below in Section 6.1. One particular public information task was conducted in 2011 since Risø DTU and FOM in 2010 took up the EFDA task of *Interactive Exhibits for the Fusion Expo*. This task was prolonged to include 2011 and it is described in Section 6.2.

Over the last couple of years a good contact has been established between Risø DTU and the national science talent center (ScienceTalenter) in Sorø. This has resulted in several talks to high school teachers and/or students. However, most importantly, ScienceTalenter received a grant to make a fusion physics master class for 25 science talents from 5 high schools. This was conducted with one initial camp for the teachers followed by two camps for the students with homework projects. This gave all a solid foundation in the field of fusion physics, and the master class was concluded by a 4 days travel to England with the main attraction being a visit to JET and MAST.

For brevity the activities are put in list form below

- Several popular lectures on fusion energy – mainly the roadshow – at high schools and at public science events.
- Assisting students from primary and high school in fusion oriented projects.
- Contact to journalists (web, newspapers, radio and TV) on fusion and ITER related news
- Continued participation in the *Scientarium* - the Panel of Experts of Ingeniøren – Engineering Weekly News Magazine

6.1 The Danish Fusion and Plasma Road Show

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As part of the ongoing public information activities, the Danish Fusion and Plasma Road Show have been created by members of Association Euratom - DTU. The show was initiated in 2007 having the Dutch Fusion Road Show from FOM-Institute for Plasma Physics Rijnhuizen as inspiration. The show was funded for three years (2007-2009) by the Danish Research Council for Nature and the Universe under the Ministry for Science, Technology and Innovation – by a total of approx. 40,000 Euro. Since the funds have ceased the show has been maintained and used for some events: The Danish National Science Festival (September 2011) and the National Day of Science (April 2011).

The objective of the road show is to inform students and the general public about present fusion energy and plasma research and in that way give them an insight and hopefully an interest in science and its uses. In particular we hope that the students get inspired by the physics and see that fusion energy research is an exciting field with many possibilities. Another important objective is to inform about the use of fusion as a source of energy, and in that way clarify the benefits and challenges of fusion power.

The show is a combination of a regular slide based presentation and a number of small experiments that demonstrate or is related to a topic described in the presentation. The experiments are intended to surprise and excite people and also work as intermezzos in the talk. This is intended to help keep people focused on the topics. In the presentation a great effort is put in simplifying the advanced topics, and it is intended to bring the involved phenomena close to people's experiences from everyday life. This is done e.g. by converting enormous numbers in strange units into meaningful sizes, and also by asking questions or giving small exercises to the audience. The show has its own website: http://roadshow.risoe.dk, where descriptions of the experiments can be found.

In the course of the road show the following experiments are conducted

- An exercise bike connected to a generator and an inverter to be able to supply household appliances with power produced by the bike. This is a very popular experiment, where volunteers in the audience can get a feel for how much we should work to cover our consumption.
- Jacob's Ladder: Plasma created by 10.000 V between two copper wires
- Plasma in a microwave oven: Example of a RF generated plasma
- A ball on a rotating disc/turntable: Ball will move like a charged particle in EM-field
- Smoke rings: Example of the torus shape
- Electromagnet and compasses: Example of electricity generating a magnetic field
- Eddy currents in a copper plate with a strong magnet: Example of the connection between temperature and conductivity
- Superconductor – levitated magnet above superconductor
- Plasma ball lamp

6.2 Interactive Exhibits for the Fusion Expo

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FOM and Risø DTU jointly took up the EFDA task WP09-PIN-INTEX “Creating interactive exhibits for Fusion Expo”. The aim of the task is to create new and more interactive exhibits for the Fusion Expo within a number of categories. It is a multistep task, where inspiration and ideas were explored and discussed.

A range of ideas have been developed and prioritized, and the high priority ideas have been described in greater detail. All the selected exhibits have been ordered and most are already created and in the Fusion Expo.

The task has successfully been finalized with a final report submitted in December 2011.

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